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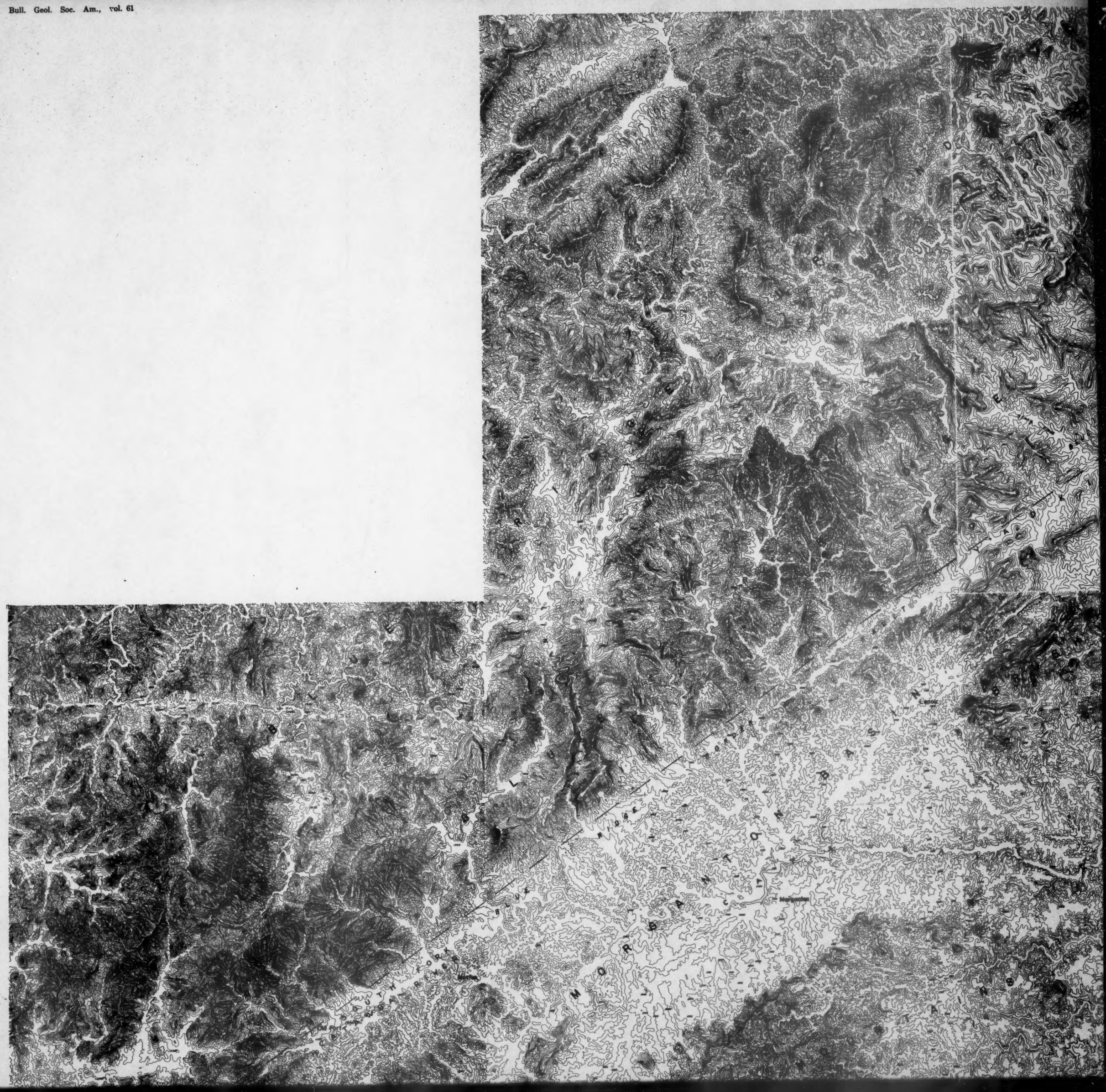
BLUE RIDGE MOUNTAINS
SOUTH MOUNTAIN
Catoctin
Hagerstown
Martinsburg
Old Fort
Paddy Mt.
Tuscarora Mt.
Warm Springs Ridge

BLUE RIDGE MOUNTAINS
BLUE RIDGE FRONT
BLUE RIDGE BORDER FAULT
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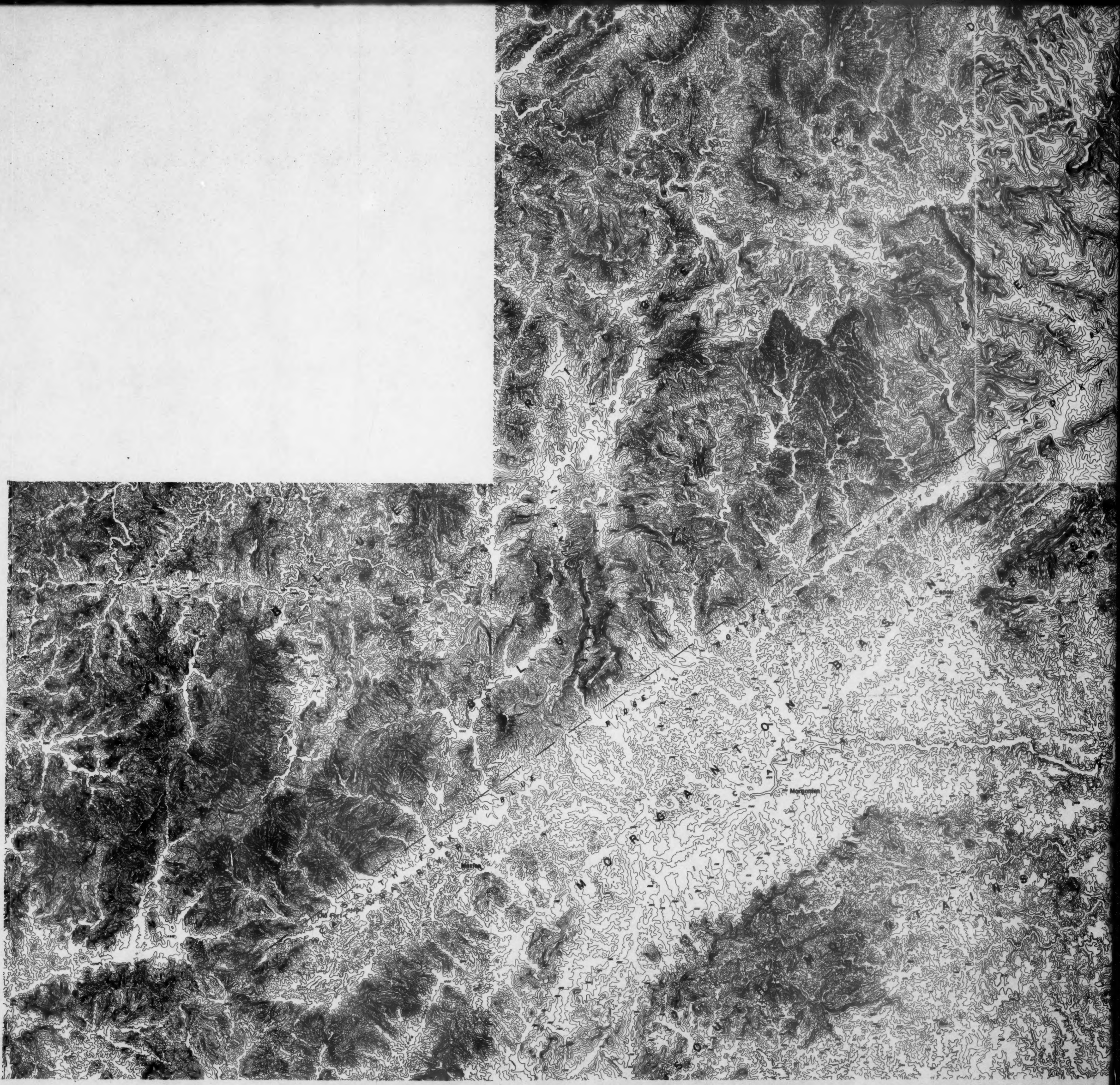

TOPOGRAPHIC MAP OF AREA ALONG BLUE RIDGE SCARP AND UPPER PIEDMONT IN WESTERN NORTH CARO

GRAPHIC MAP OF AREA ALONG BLUE RIDGE SCARP AND UPPER PIEDMONT IN WESTERN NORTH CAROLINA

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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BLUE RIDGE FRONT—A FAULT SCARP

By William A. White

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Abstract

The present Blue Ridge scarp seems to have been produced by a late Tertiary normal fault—the Blue Ridge border fault. Evidence of its existence can be found along an almost straight line extending about 700 miles from the vicinity of Gainesville, Georgia, to northwestern New Jersey.

Throughout much of its length, the Blue Ridge border fault seems to have utilized pre-existing structures of an older Triassic fault zone which borders the Blue Ridge scarp on the east.

The Asheville peneplain of the upthrown fault block is considered correlative with the Piedmont peneplain on the downthrown block. Both are probably correlative with the Schooley peneplain. The Asheville surface descends gradually via the Dahlonega Plateau from elevations approximating 2100 feet on the strath of the French Broad River near Brevard, North Carolina, to coalescence with the Piedmont surface southwest of Hightower, Georgia, at elevations approximating 1200 feet.

The higher mountains of the Blue Ridge Upland are pre-fault features, and such outlying ranges as the Brushy and South mountains of the upper Piedmont of North Carolina are their equivalents on the downfaulted block.

The higher mountains of the Southern Appalachians are on the upfaulted block in the region of greatest uplift. The southwestern extension of the Southern Appalachians beyond the end of the fault was not uplifted.

Introduction

The Blue Ridge scarp, a persistent and simple topographic feature, extends 550 miles from Georgia to Pennsylvania in a single, continuous, and nearly straight line. From its southwestern extremity near Gainesville, Georgia, to the vicinity of Roanoke, Virginia, it is a true scarp at the edge of a plateaulike upland, with crest elevations which rise progressively from the Piedmont level of 1000 feet at its southwestern end to a maximum elevation of 4000 feet in the vicinity of Blowing Rock in Watauga County, North Carolina. Northward from Blowing Rock the crest level falls gradually to an elevation of about 2500 feet in Floyd County, south of Roanoke, Virginia.

This scarp forms the eastern edge of the Blue Ridge Upland[1] which has maximum local relief of 5000 feet encompassed largely within elevations above those of adjacent crest levels on the scarp. With very minor exceptions the Blue Ridge Upland has not been dissected by the young streams which flow eastward down the scarp.

The abruptness of the scarp is striking. Streams flowing east from its crest fall as much as 3000 feet in 1 to 10 miles; yet at the foot of the scarp they suddenly enter broad graded valleys with well-developed flood plains which, in the upper Piedmont of North Carolina, have elevations of approximately 1200 feet. These streams drop only about 800 feet in the next 150 miles to the previously effective base level at the inland edge of the Coastal Plain; or 1200 feet in the 300 miles to the present coast.

North of Roanoke the Blue Ridge is no longer a scarp at the edge of a plateau but a true ridge, as its name implies. It is usually narrow but has old erosion surfaces preserved as flat summits throughout much of its length. It is breached by the three principal streams of the region—the Roanoke, James, and Potomac—which traverse it in narrow, steeply incised water gaps. Aside from these gaps, the crest levels of the scarp tend to descend northward to the Potomac River where they reach a minimum of about 1500 feet. North of the Potomac, they gradually rise again.

Lithologic and topographic conditions above and below the Blue Ridge scarp are remarkably similar when one considers the abrupt, straight, and persistent nature of the topographic break. Throughout most of their length, the Blue Ridge Upland, the Piedmont, and the dissected scarp have very similar metamorphic rocks. Also the topography of the upper Piedmont below the scarp resembles that of the Blue Ridge Upland above the scarp. In both, wide open straths separate mountain masses of considerable local relief. The Morganton Basin of the North Carolina Piedmont, for example, is topographically similar to the Asheville Basin of the Blue Ridge Upland but 600 to 800 feet below it.

It would seem incongruous to explain such a persistent topographic break solely by erosion when it is closely paralleled by the contact between two major lithologic provinces. The Paleozoic rocks are notably less resistant to erosion than the Precambrian metamorphics; yet no such regular or continuous topographic feature as the Blue Ridge scarp is developed along the line of contact between the two. On the contrary, in several places both Paleozoic and crystalline rocks are beveled by the same peneplain remnants, as in the northwestern counties of North Carolina and adjacent parts of Virginia as well as in the area around Middleburg, Virginia.

[1] In the topographic provinces defined by Fenneman (1938) the part of the older Appalachians west of the piedmont is called the Blue Ridge Province. However, in this paper the Blue Ridge scarp must be distinguished from the general upland area above it. The term "Blue Ridge Upland" has therefore been introduced for that part of the Blue Ridge province above and northwest of the scarp.

Acknowledgments

The writer acknowledges his indebtedness to Dr. J. L. Stuckey, State Geologist of North Carolina, who made possible many of the field observations in western North Carolina and near-by areas in adjoining States.

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Mr. F. M. Orsini, Southeastern Regional

Chief of the Cartographic Division of the Soil Conservation Service, U. S. Department of Agriculture, was very co-operative in providing aerial photographs.

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Many observations pertinent to this study were made while doing the field work for another study which was supported by a grant from the Carnegie Research Fund.

Earlier Theories of Origin for the Blue Ridge Scarp

Davis (1904), supported by Johnson (1906), suggested that the scarp of the southern Blue Ridge is the normal development at the divide between the two peneplains of stream systems of different length working simultaneously to the same base level. He thought the shorter Atlantic drainage should have been able to reduce its drainage area to a peneplain, the headward edge of which should have been lower than the adjacent edge of the opposing peneplain developed by the longer streams flowing southwestward to the Gulf of Mexico. He thought a sharp escarpment should mark the divide between these two peneplains.

This argument appears inadequate when one considers the extreme differential between the erosive power of the young streams flowing eastward down the steep scarp and the graded streams flowing westward on the Blue Ridge Upland above the scarp. Without structural control (such as a resistant caprock in a sequence of horizontal strata), a steep scarp could not form at the divide between two simultaneously developed peneplains; the young headwater reaches of the shorter stream system would extend themselves headward into the adjacent upland much more rapidly than their lower, graded reaches could reduce the land mass to extend the peneplain headward. If a stream system has not been affected by structural or diastrophic factors, its profile should show a gradual steepening toward the headwaters rather than a well-developed peneplain covering virtually the entire drainage area but abruptly terminated within "a stone's throw" of the divide by a nearly vertical scarp with young streams flowing down it.

A scarp such as that of the Blue Ridge is extremely vulnerable to dissection, as both Davis and Johnson recognized. If two adjacent peneplains were developing simultaneously, the shorter drainage would extend its headwaters persistently westward until, when peneplanation was attained by both drainages, the divide would be approximately on a line bisecting the combined drainage areas and making the distance to sea level about equal in both directions. Davis apparently recognized this as the ultimate adjustment of divides, but seems to have erred in assuming that peneplanation of the shorter drainage areas could approach the divide so closely before the adjustment had been made.

Headward extension in the shorter and stronger drainage would doubtlessly take place over a wide zone with long spurs extending seaward on the interfluves. Streams dissecting an upland of great relief by headward erosion characteristically insinuate their gorges headward for long distances before the interfluvial areas are reduced to a peneplain. Furthermore such dissection produces interfluvial spurs that do not terminate on a straight line but are highly irregular in plan, some extending much farther downstream than others. Davis (1909, p. 738) realized this, for he says:

> "Viewed in detail the base of the escarpment is sinuous in a high degree, with numerous branching spurs that advance between well-carved amphitheatres; the spurs gradually fade out forward instead of being abruptly terminated at a well-defined base line."

Actually, the spurs of the Blue Ridge scarp tend to terminate along a straight line, particularly in the North Carolina section of the scarp—the section Davis was describing. This straight line is readily seen on Plates 1 and 2.

In further discussion of Davis' idea of a "break-joint" between two contemporaneous peneplains working to the same base level, it may be observed that the straths of the west-flowing streams on the Blue Ridge Upland are not immediately controlled by the level of the Gulf of Mexico, but rather by the level of the Appalachian Valley of eastern Tenessee. In Tertiary time they were probably controlled

by a coast located where the Tennessee River enters the Gulf Coastal Plain. This point is little farther from the Blue Ridge scarp than are comparable points where the southeast-flowing streams enter the Atlantic Coastal Plain.

Considering this last fact it becomes obvious that if the Blue Ridge were wholly an erosional feature the west-flowing streams of the Blue Ridge Upland should now be graded down to the level of the Appalachian valley into which they flow. The Paleozoic limestones should have been reduced to grade far more readily than the crystalline rocks of the Piedmont and, if the two surfaces were developed simultaneously by erosion, the narrow belt of crystallines (Blue Ridge Upland) drained to the Appalachian Valley would have been reduced more readily than the lithologically similar but much broader Piedmont. Under such circumstances the headwater straths of the west-flowing streams of the Blue Ridge Upland should be at about the same level as those of the east-flowing streams of the Piedmont.

Actually—far from being a peneplain adjusted to sea level—the Asheville surface is rapidly being dissected by the young west-flowing streams which are pushing gorges eastward from the western scarp of the Blue Ridge Upland where it rises above the Appalachian Valley of Tennessee. Witness, for instance, the gorges of the Hiwassee, the Little Tennessee, the Pigeon, the French Broad, the Nolichucky, the Watauga, and the Doe. On the other hand, the east-flowing streams of the Piedmont show no such rejuvenation except above the line where they enter the Blue Ridge Scarp. This would suggest that the west-flowing streams have undergone an uplift which has not affected the east-flowing ones, and therefore the Piedmont and Asheville surfaces cannot be in contemporaneous adjustment to sea level.

Moreover, had the Blue Ridge scarp developed by headward erosion, it would seem requisite that it be a divide throughout its entire length, but it is not. Extensive areas of the upland behind the scarp are drained by such east-flowing streams as the Chattooga and Tallulah, the Linville, the Roanoke, the James, and the Potomac. Also the streams of the Mississippi system are longer than the opposing streams of the Atlantic slope throughout the length of their divide. Therefore, if the "break-joint" hypothesis were applicable to the Blue Ridge scarp in Georgia and the Carolinas, it should be equally applicable in Virginia, Maryland, and Pennsylvania. Although the Blue Ridge persists into these areas, it is increasingly remote from and east of the major divide. The area behind it which is drained by the east-flowing streams is so complex in topography as to preclude any comparison to the well-developed peneplain of the piedmont in the Carolinas and Georgia.

Further argument against Davis' theory may be based on the existence of such eastward-flowing streams as the Linville and Green rivers in North Carolina and the Dan River in southern Virginia. All these streams rise west of the scarp on the Blue Ridge Upland and flow through graded valleys with wide flood plains until they reach the head of rejuvenation near the crest of the scarp. There they cascade into steep-walled gorges and emerge at the foot of the scarp, again in well-graded valleys. The configuration of the upland topography around the graded headwaters of the Linville and Dan rivers in the Blue Ridge Upland precludes their being captured fragments of former west-flowing drainage. In each instance the head of the rejuvenated gorge section has not been extended much farther westward than the general crest line of the scarp. It is obvious that the scarp could not have been produced by the headward erosion of such streams, for their headwater reaches are above it and are meandering at grade on an old erosion surface. This relationship is exemplified by the Saluda, North Carolina, sheet which shows the Green River; the Morganton and Cranberry sheets of North Carolina which show the Linville River; and the Stuart, Virginia, sheet which shows the Dan River. The Linville Valley may also be seen in Plate 1. Similar streams in Georgia which have undissected headwater reaches on the western edge of the Dahlonega Plateau are discussed below.

A more plausible location for the divide between comtemporaneously developed peneplains can be found in the closely equivalent headwater flood plains of opposing Atlantic and Gulf drainages on the Blue Ridge Upland. Outstanding examples are Rabun Gap on the Walhalla, Georgia—South Carolina—North

Carolina, sheet, and the divides between certain headwater tributaries of the Green River and the opposing tributaries of the French Broad River on the Saluda, North Carolina—South Carolina, sheet. In both instances the divide is in a wide, open strath shared by both streams. Figure 2 shows a profile along the headwater strath of the west-flowing Little Tennessee River, through Rabun Gap, and down the headwater strath of Stekoa Creek, the opposing east-flowing drainage.

Hayes and Campbell in an early paper (1894) and Campbell in personal communications to Davis (1904, p. 222) suggested that the Blue Ridge scarp is an eroded monoclinal flexure in which the Piedmont was depressed to its present elevation and the Blue Ridge Upland was elevated.

This theory correlates the old erosion surfaces above and below the scarp in what the writer believes is their true relationship. Thus the Asheville surface of the Blue Ridge Upland is correlated with the Piedmont surface or the strath terrace of the Catawba River in the upper Piedmont. The structure of the metamorphic rocks is so complex that it would readily conceal any late open flexure, and any supporting evidence for it would have to be topographic. However, there seems to be no evidence of such a flexure in the present topography. On the contrary, there is a very sharp and straight base line at the foot of the scarp. Along this line, the steep slopes of the scarp intersect the level surface of the Piedmont. Whatever the nature of the structure responsible for the scarp, plausibly it should be localized along this line.

Merely on the grounds of mechanical plausibility it would seem improbable that rigid crystalline rocks such as those exposed in the Blue Ridge should support, under surface conditions, a flexure of requisite abruptness to explain the scarp with its straight base line and precipitous change of slope. It seems more probable that a definite fracture should occur in the manner of a steep-angle normal fault.

Apparently Campbell changed his ideas in more recent years, for Fenneman (1938, p. 189) in a footnote refers to a personal communication in which Campbell expressed the opinion that the scarp of the southern Blue Ridge is the result of faulting. Such an opinion would agree with the writer's findings, although in another footnote Fenneman (1938, p. 138) quotes a further communication from Campbell which suggests that the monadnocklike outlying hills of the upper Piedmont are also faulted up in relation to the Piedmont surface. With this the writer would not agree, unless Campbell meant resequent fault-line scarps.

Wright has written extensively on the geomorphology of the Blue Ridge, but his observations on its origin are largely an analysis of the literature. One paper (1927) considers, with much skepticism, the possibility of faulting. This paper is discussed below in the section on Opposing Opinion.

Normal Faulting in the Vicinity of the Blue Ridge

To some readers it may seem heterodox to introduce the idea of extensive normal faulting in discussing the Southern Appalachians. However, the Palisades disturbance is well recognized, and the border faults of Triassic basins closely parallel the Blue Ridge front in Pennsylvania, Maryland, and northern Virginia. They are also found at the eastern edge of the Reading Prong, which is structurally comparable to the Blue Ridge.

More local support for the idea of extensive normal faulting in Virginia may be had from the Catoctin Mountain border fault which is shown on the Geologic Map of Virginia (Stose, 1928) as extending completely across the State roughly parallel with the Blue Ridge front and approaching it rather closely near the North Carolina boundary. Furcron (1939) has shown the presence of many normal faults in the vicinity of Warrenton, Virginia, and Keith (1892–1893) assumed their presence in the Catoctin belt: "Doubtless Newark structures are present in the Catoctin Belt, but the means are not at hand for detecting them." Watson and Cline (1913, p. 347) observed many normal faults in the Cambrian of northern Virginia:

> "The results obtained in the Fauquier-Culpepper slate area strengthen the probability of a wider distribution of Newark structures in the Appalachian belt than has formerly been supposed. Since the crystalline rocks of the Piedmont belt are here cut extensively by normal faults in various directions, which are made recognizable only by a thin mantle of well defined Cambrian strata, and since the

writers and others have observed similar structures in the Shenandoah group of limestones in the Great Valley province west of the Blue Ridge, it is very likely that further investigations will reveal normal faulting more widely distributed in the Appalachian province."

Of course, all these writers were speaking of faults believed to be of Triassic date, but later movements are suggested by the occurrence of earthquakes of considerable force in the vicinity of Buckingham, Virginia, not far east of the Blue Ridge border fault. Taber (1913) credited them to motion on normal faults.

Taber (1916) also described an earthquake in the Southern Appalachians which occurred on February 21, 1916. His map shows an epicentric line parallel with and somewhat west of the Blue Ridge border fault in northwestern South Carolina.

Neumann (1924) recorded an earthquake of intensity 5 on October 20, 1924, with its epicenter on the trace of the Blue Ridge border fault west of Pickens, South Carolina.

Fault Zone in North Carolina, South Carolina, and Georgia

As the peculiarities of the Blue Ridge and its environs became known to the writer, he concluded that their only plausible explanation lay in the presence of a normal fault at the foot of the spurs of the scarp. Field examination in 1945–1948 revealed evidence suggesting the presence of the fault at the expected location, and study of regional mosaics of aerial photographs, together with composite topographic maps, suggested attendant structural conditions of much interest.

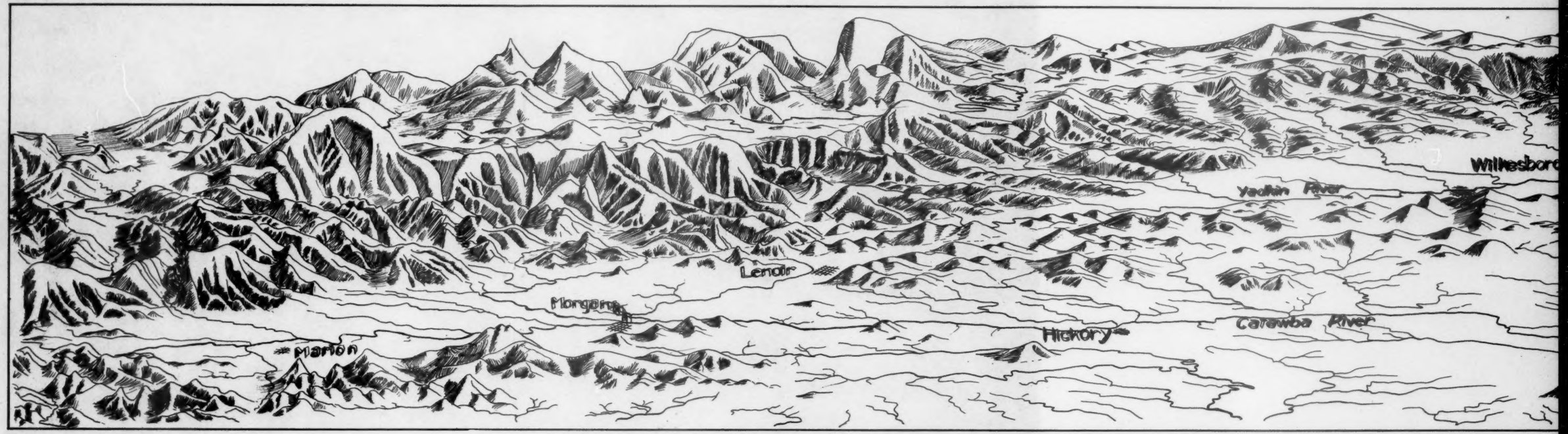
The writer's general conclusions are: A Triassic fault basin seems to parallel the scarp on the east. What appears to have been the western border fault of this basin was reactivated, probably during the late Tertiary, to create the present Blue Ridge scarp, which is a normal-fault scarp rather extensively modified by erosion.

The later, reactivated faulting seems to have been much simpler than the original Triassic structures. With a few unimportant exceptions, it apparently was limited to a single break along one essentially straight line, which is offset at irregular intervals to the left. This apparent fault, along which the later movement took place, appears to be responsible for the Blue Ridge scarp. It is called the "Blue Ridge Border fault."

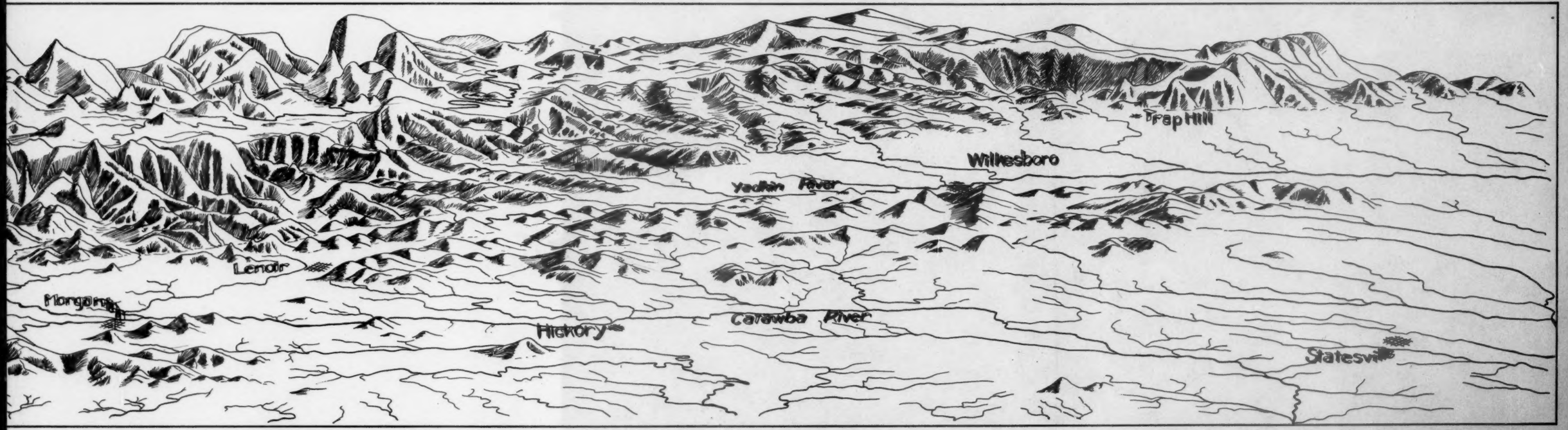
In North Carolina a Triassic basin seems to have extended northeastward along the foot of the scarp from Old Fort in MacDowell County to the vicinity of the confluence of Stony Creek with the Yadkin River (Wilkesboro, North Carolina, sheet) (Pl. 1). There, the old fault swings increasingly eastward, diverging from the trend of the escarpment, which is offset a few miles to the northwest apparently by a cross fault. The old fault continues, in a remarkably straight line, across Wilkes and Surry counties, North Carolina, into Patrick County, Virginia, closely paralleling the western border fault of the well-known Dan River Triassic basin a short distance to the east.

Northeast of Walnut Cove in Stokes County, North Carolina, the Dan River basin contains continental sediments of the Newark Series and in Davie County, North Carolina, a small isolated patch of Triassic sediments apparently represents a dissevered remnant of a much larger sediment-filled basin which formerly was coextensive with the Dan River basin to the northeast. The Dan River basin is long and narrow, and a southwestward extension of the trend of its northwestern border fault would intersect the Davie County area. Therefore, it is plausible that Triassic sediments were formerly present throughout the 25—mile gap between the present Dan River and Davie areas. Considered jointly, these two sediment-filled basins have a slightly curvilinear trend closely parallel with the trace of the Blue Ridge border fault 25 miles to the northwest, which supports the concept of Triassic structures at the foot of the Blue Ridge scarp. Extensive areas of low relief along the foot of the scarp are bounded on the northwest by the trace of the Blue Ridge border fault and give every indication of being former Triassic basins similar to the Dan River-Davie County basin, except that any sediments they may have contained are now wholly eroded. These areas may be noted on Plate 1 as the Morganton and Wilkesboro basins.

The traces of these old Triassic faults are reflected in the courses of the streams they control. A pronounced trellis drainage prevails



TOPOGRAPHIC SKETCH OF AREA ALONG BLUE RIDGE BORDER FAULT IN WESTERN NORTH CAROLINA



TOPOGRAPHIC SKETCH OF AREA ALONG BLUE RIDGE BORDER FAULT IN WESTERN NORTH CAROLINA

which can be seen in the areas marked Morganton and Wilkesboro basins (Pl. 1).

The drainage pattern of the Blue Ridge scarp does not reflect these structures which control the pattern in the basins at its foot. The trellis pattern gives way at the fault trace to the more northerly trending valleys of the scarp. These north-trending drainage lines are also strongly developed in the valleys of Hunting Creek and Little Hunting Creek in the Brushy Mountains. Appearing thus in parallel development on both sides of the Wilkesboro basin but not in it, they support the idea that it is a descrete structural entity.

The western border fault of the old Triassic zone appears at the foot of the Blue Ridge scarp and controls the South Fork of the Catawba River from Old Fort in MacDowell County, North Carolina, to Lake James in Burke County. Its influence is also seen in the localization of sections of the valleys of minor tributaries of the Catawba River at the foot of the scarp in the Johns River drainage area of Burke and Caldwell counties, North Carolina. Here these streams flow at right angles to their master streams localized by the Blue Ridge Border fault and paralleling the Blue Ridge scarp. Throughout this distance the Blue Ridge border fault seems to have been localized by reactivation of the marginal Triassic structure, and its location is well marked by its influence on the drainage.

From Patterson Mill (Cranberry, North Carolina-Tennessee, sheet) to the vicinity of Stony Creek (Wilkesboro, North Carolina, sheet), the Blue Ridge border fault follows the same ancestral structure, but the principal drainage of the area, the Yadkin River, seem to follow a parallel one a short distance to the southeast. This parallel structure curves slowly but increasingly to the east, and the river follows it for about 60 miles to the vicinity of Siloam in Surry County, North Carolina. Near the confluence of Stony Creek with the Yadkin River, the Blue Ridge border fault is offset a few miles to the left (Pls. 1, 2), but the ancestral Triassic structure which it had followed southwest of Stony Creek continues on to the northeast along the same straight line. It appears a short distance to the northwest of the Yadkin River (Pl. 1), diverges slowly from the course of the river, and maintains a straighter and more northeasterly strike as the river valley curves away increasingly to the east.

M. J. Mundorff (personal communication) has noted similar structural control of small tributaries of the Yadkin in crystalline rocks near East Bend in Yadkin County, North Carolina, which he ascribes to Triassic faults associated with the Dan River basin.

Northeast of the Stony Creek offset, the Blue Ridge scarp continues on a straight course approximately parallel with the unreactivated Triassic fault on the southeast. The trace of the Blue Ridge border fault lies closely along its foot marked by the line along which the spurs terminate.

This trace of the Blue Ridge border fault transects quartzites, quartz-biotite gneisses, schists, and, in one locality, granites. The spurs, which terminate along the straight base line so graphically shown in Plate 1, are composed of these different rocks. This fact precludes the idea that the scarp represents any erosional feature which has etched out a less resistant stratum and left a resistant one holding up the ends of the spurs. Moreover, the fact that some of the spurs in the northern part of Wilkes County, North Carolina (near Hanks Store, Dockery, and Trap Hill on the Wilkesboro, North Carolina sheet), are held up by granite militates against the idea that the locus of the base line is stratigraphic. Where the fault trace parallels a resistant quartzitic phase of the metamorphics represented by Rip Shin Ridge in the southwestern corner of the Wilkesboro, North Carolina, sheet, the spurs held up by this strongly planar rock have "hammer-headed" or "winged" ends, but, where the spurs are held up by the upfaulted granite, they are narrow and pointed without any such lateral extensions.

From Marion to Old Fort the ancestral Blue Ridge border fault does not seem to have been reactivated. It extends southwestward into a valley which forms a re-entrant into the scarp and is occupied by the South Fork of the Catawba River. The southern continuation of the scarp is offset to the east at this point and is apparently localized by parallel structures a few miles southeast of the Old Fort re-entrant.

Parallel with the Blue Ridge scarp and 5 to 10 miles east of it on the east side of the Triassic fault basin, a number of outlying mountain

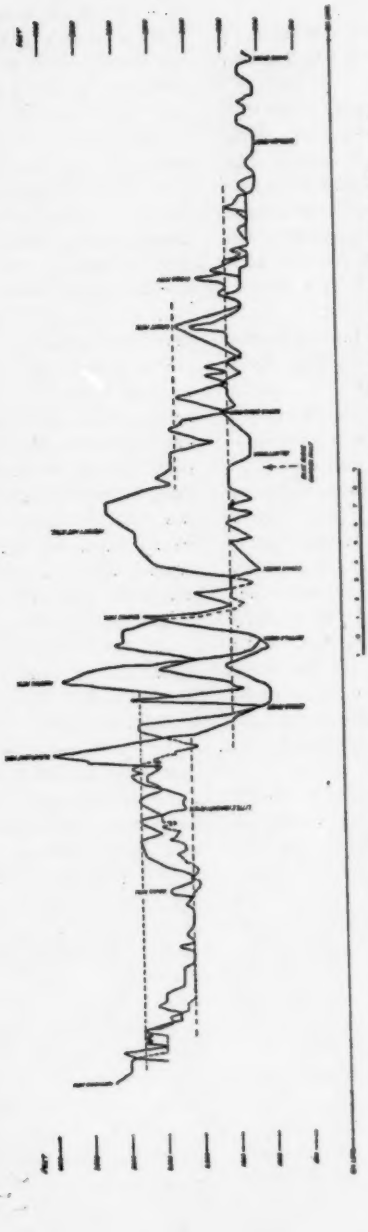


FIGURE 1.—PROJECTED PROFILE FROM ASHEVILLE BASIN OF BLUE RIDGE UPLAND TO MORGANTON BASIN OF PIEDMONT
Note two levels of ridge accordance, both above and below the Blue Ridge border fault.

ranges appear to be topographic correlatives of the higher mountains on the Blue Ridge Upland above the scarp. In North Carolina, these outlying ranges are exemplified by the South Mountains of Burke and Rutherford counties and the Brushy Mountains of Caldwell, Alexander, and Wilkes counties. Similar ridges appear in the same relation to the Blue Ridge scarp in Virginia.

The South Mountains and the Brushy Mountains have straight base lines on their northwestern flanks, facing the Blue Ridge (Pl. 1). This suggests that their northwestern edges have been determined by fault lines, possibly the eastern border faults of the old Triassic basins. On the other hand, the southeastern flanks of the same outlying ranges are characteristically irregular in plan. Instead of having straight-line edges extending northeast-southwest, as do the northwest sides, they are embayed by many long re-entrant valleys of random orientation. The spurs extend differentially into the Piedmont. Off their ends, it is common to find monadnocks.

This is the normal manner in which a mountain range produced by the fluvial cycle operating on crystalline rocks would be expected to descend into its piedmont, and it is believed that such a relationship of mountains to piedmont would have resulted at the immediate foot of the Blue Ridge scarp, had it been produced by headward erosion of streams unaided by structural control. However, the foot of the Blue Ridge meets the Piedmont in a linear scarp, with a straight base line across which no spurs extend.

The writer considers these facts strong support for his belief that the original eastern edge of the mountains is represented by the eastern limits of the present outlying ranges, whereas the foot of the present scarp represents the trace of the Blue Ridge border fault, the throw of which is directly responsible for the relief of the scarp.

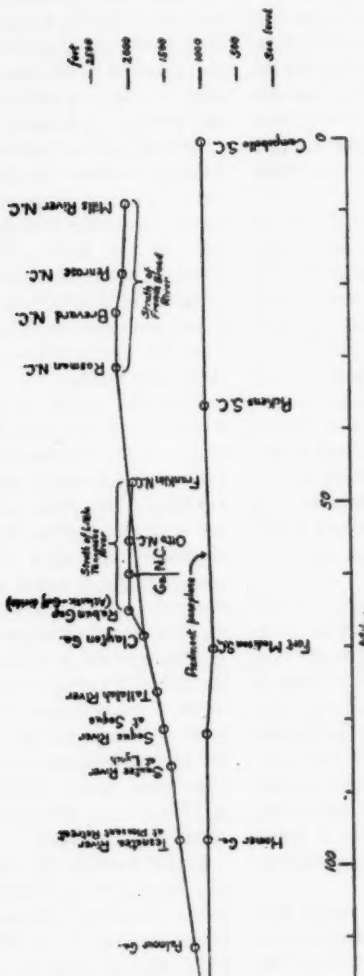
Further evidence for late normal faulting is found in the elevations of the outlying ranges, such as the Brushy Mountains and South Mountains of North Carolina, which in general rise above the surrounding Piedmont surface about the same amount that the mountains of the Blue Ridge Upland rise above the late straths of that province, such as the Asheville peneplain. That is, topographic prominences on both the Piedmont and the Blue Ridge Upland are ancestral mountains on the now-severed parts of a surface which was formerly continuous, probably in Schooley time (Fig. 2).

This suggests correlation of the Asheville and Piedmont surfaces. At places these two surfaces come into close geographic proximity on opposite sides of the fault line. At Racoon Mountain, on the Saluda, North Carolina-South Carolina, sheet, the Asheville surface, with an elevation of 2200 feet, at the head of Pulham Creek, is no more than half a mile horizontally from the Piedmont-level strath of the Green River near Fishtop.

Fenneman (1938, p. 192) noted an intermediate level seen from Blowing Rock (Cranberry, North Carolina-Tennessee, sheet) between the Subsummit peneplain, which forms the Blue Ridge crest level at that point, and the Piedmont surface. It is very poorly preserved and somewhat difficult to see, but it extends to points rather close to the Piedmont and very probably represents an upfaulted and maturely dissected former part of the Morganton Basin, which would now be correlative with the Asheville surface. A possible extension of it to the northeast may be noted in the rather level ridge tops on the ends of the spurs of the Blue Ridge scarp between Patterson on the Cranberry, North Carolina-Tennessee, sheet and Skull Camp Mountain on the Yadkinville, North Carolina, sheet.

Figure 3 shows the genetic relationship of this surface to the Piedmont level. Figure 3 (No. 1) shows the area as it may have looked before reactivation of the Blue Ridge border fault. The Ancestral Appalachians compose a wide belt of residual resistant masses which have been penetrated by large re-entrant straths of what the writer is inclined to regard as the Schooley peneplain. Partially dissected remnants of an older surface, the Subsummit, are preserved. The site of the present Blue Ridge fault scarp is occupied by an older resequent fault-line scarp which is discontinuous because the Schooley strath has cut back into it locally. The South and Brushy mountains are shown in the foreground.

Immediately after reactivation of the Blue


feet
— 2500
— 2000
— 1500
— 1000
— 500
— Sea level
Campobello S.C.
Mills River N.C.
Brevard N.C.
Rosman N.C.
Flat Rock N.C.
Hendersonville N.C.
Saluda N.C.
Tryon N.C.
Columbus N.C.
Rutherfordton N.C.
Spindale N.C.
Forest City N.C.
Shelby N.C.
Kings Mountain N.C.
Gaffney S.C.
Blacksburg S.C.
Fort Mill S.C.
Chester S.C.
Lancaster S.C.
Camden S.C.
Columbia S.C.
Winnsboro S.C.
Blair S.C.
Prosperity S.C.
Newberry S.C.
Greenwood S.C.
Abbeville S.C.
Elberton Ga.
Royston Ga.
Toccoa Ga.
Clayton Ga.
Dillard Ga.
Mountain City Ga.
Tallulah Falls Ga.
Clarkesville Ga.
Toccoa River at Dial
Tugaloo River at Lavonia
Savannah River at Calhoun Falls
Tugaloo River at Tugaloo State Park
Savannah River at Hartwell
Tallulah River
Savannah River at Seneca
Chattooga River at Lula
Tugaloo River at Bowman
Tugaloo River at Madison Bridge
Tugaloo River at Belton Bridge
Tugaloo River at Pendleton
Tugaloo River at Piedmont Bridge
Tugaloo River at Piedmont Retreat
Tugaloo River at Piedmont Falls
Tugaloo River at Piedmont Shoals
Tugaloo River at Piedmont Rapids
Tugaloo River at Piedmont Ford
Tugaloo River at Piedmont Ferry

Ridge border fault (Fig. 3, No. 2) the old, discontinuous fault-line scarp became a continuous young fault scarp, but the places where the older fault-line scarp was uplifted show a higher crest level than do those where the re-entrant Schooley straths were elevated. These upfaulted re-entrants have been dissected (Fig. 3, No. 3) to become the intermediate level described by Fenneman.

The ancestral fault-line scarp of the Blue Ridge is similar to the present fault-line scarps on the northwestern flanks of the outlying South and Brushy mountains. Both are discontinuous with large re-entrant and even transecting straths in contrast to the continuous and unbroken present Blue Ridge scarp. Since the topography on both sides of a fault-line scarp is produced by the same erosion cycle, there is no reason why either side should stand up as a continuous highland, except where it is supported by rocks of greater resistance to erosion. Therefore, in a situation like that of the Blue Ridge zone, where essentially similar, but locally variant, metamorphic rocks are found on both sides of the fault trace, it would be very improbable that a consistent and unbreached highland such as the present Blue Ridge scarp should be preserved on either side. The more plausible expectation would be like the situation in the outlying ranges where large transecting straths such as that of the Catawba River connect correlative surfaces on opposite sides of the highland. Before reactivation of the Blue Ridge border fault, some of the piedmont level straths such as that of the French Broad River (now upfaulted to become the type area of the Asheville peneplain) seem to have transected the Ancestral Appalachians in such manner, having been coextensive with both the piedmont on the east and the Ridge and Valley province on the west. Similar situations can be found elsewhere along the Blue Ridge Upland such as at Rabun Gap in Georgia.

In several places the older and higher peneplain of the Blue Ridge Upland (Subsummit?) forms the crest of the Blue Ridge scarp, and the Blue Ridge border fault apparently transected it. At Cold Branch Mountain on the Pisgah, North Carolina-South Carolina, sheet, the Subsummit surface on the Blue Ridge Up-

FIGURE 3.—SEQUENCE OF TOPOGRAPHIC SKETCHES SHOWING GEOMORPHIC EVENTS IN MORGANTON BASIN

Looking north.

(1) Vicinity of Morganton Basin, N. C., in Schooley time, showing Ancestral Southern Appalachians. South Mountains in foreground. Morganton Basin in left and center of middle distance. Brushy Mountains in middle distance to right. Trace of ancestral Blue Ridge border fault, before Tertiary reactivation, shown by broken line at front of discontinuous fault-line scarp which is penetrated by large peneplaned salients of the Morganton Basin.

(2) Same, immediately after reactivation of Blue Ridge border fault. The young fault scarp is higher where it has elevated the former remnants of the old fault-line scarp. Dissection has begun on the uplifted salients of the peneplaned Morganton Basin.

(3) Same, as seen today after erosion of Blue Ridge fault scarp. Remnants of ancestral fault-line scarp of Schooley time are still obscurely manifest in higher parts of scarp. Former salients of Morganton Basin have been so intimately dissected that only a general accordance of ridge tops manifests their former planate condition.

land at an elevation of about 3000 feet comes to the edge of the scarp within a mile horizontally of the Piedmont surface below. Likewise on the Morganton, North Carolina, sheet, Shortoff and Linville mountains have flat tops at about the same elevation (3100 feet) as the strath of the Linville River in the graded part of its course on the Blue Ridge Upland, above the head of rejuvenation at Linville Falls (Fig. 4). Shortoff Mountain and Linville Mountain appear on opposite sides of the Linville Gorge, just above its debouchment onto the peneplaned surface of the Piedmont. Their crests are held up by the extremely resistant Irwin quartzite, which extends horizontally from Linville Falls, at the head of the gorge, to the crests of these mountains at its foot. On the eastern flanks of Shortoff Mountain, the quartzite suddenly assumes a much steeper attitude and dips steeply to the southeast as though dragged down by the old Triassic border fault although this would seem unlikely because of its extremely massive and competent nature.

The fault trace is at the foot of this dip slope at the eastern base of Shortoff Mountain, and it is less than a mile from the nearest remnant of the upfaulted part of the surface, on its summit, to the downfaulted part, or Piedmont.

The difference in elevation between these upfaulted remnants of the Subsummit peneplain and the Piedmont surface is probably not a measure of the throw of the Blue Ridge border fault, for the Asheville peneplain rather than the Subsummit seems to be the upfaulted correlative of the Piedmont surface, and even before reactivation of the fault there was probably a resequent fault-line scarp here between the Subsummit surface on the tops of Shortoff and Linville mountains and the Asheville surface below them to the east.

The gorge of the Linville River between Linville Falls and the foot of the Blue Ridge scarp appears to be a two-cycle valley despite its steepness. The vertical walls of the highly resistant quartzite are not involved in the inner gorge except for a few miles below the falls at its head. They are some distance apart throughout most of the length of the valley, and the V-shaped walls of the inner gorge slope steeply toward the stream channel below them. Evidently this valley was graded in prefault (Schooley?) time with a flood plain developed at the Piedmont level which then was probably a short distance below the base of the quartzite walls. Thus the Linville Falls would antedate the rejuvenation which followed reactivation of the Blue Ridge border fault, but would have had

(1) Assumed appearance of Linville Gorge before reactivation of Blue Ridge Border fault. A strath has been cut back into the old fault-line scarp at Piedmont level. The resistant quartzite holds up vertical valley walls but is sapped by more facile erosion of underlying schist. Ancestral Linville Falls at head of lower (Schooley ?) strath. Older (Subsummit) strath in background above falls. The quartzite dips sharply to the southeast at the scarp.

(2) Present appearance of Linville Gorge. Former Piedmont-level strath has been uplifted by reactivation of faulting and destroyed by post-fault dissection. The falls have retreated farther upstream, and a narrow, young canyon has been cut at the mouth of the gorge in the new increment of steeply dipping quartzite which has been presented to dissection by upfaulting.

FIGURE 4.—SEQUENCE OF SKETCHES SHOWING GEOMORPHIC EVENTS IN LINVILLE GORGE

its amount of fall increased as post-fault dissection enabled the Linville River to incise the uplifted flood plain. An ancestral Linville Falls would have existed in prefault time at the head of this ancestral gorge, and the probable retreat of the falls since reactivation of the fault is only from the point where the vertical walls of quartzite converge on the river channel. This small retreat is about what one would expect by comparison with the greater amount of retreat of near-by consequent streams developed on the scarp, for they have been working in the less resistant schists rather than in the extremely refractory quartzite.

There is, of course, a shorter and younger canyon in the quartzite at the lower end of the gorge, for here post-fault dissection has cut into the quartzite where it dips sharply down toward the fault trace. The sequence of events described here is shown diagrammatically in Figure 4.

Correlation among the three peneplains involved in the North Carolina area is complicated because the vertical interval between the highest (Subsummit) and the intermediate (Asheville) is approximately the same as the interval between the intermediate and the lowest (Piedmont). In other words, the interval between the Subsummit Peneplain and the Asheville Peneplain is about equal to the throw of the Blue Ridge border fault. The elevation of the Subsummit remnants is about 2700 feet in the Asheville area; that of the Asheville surface, about 2100 feet; the difference between them about 600 feet. The elevation of the Piedmont peneplain at the foot of the Blue Ridge scarp in the Morganton Basin of North Carolina is about 1400–1500 feet; the difference between these elevations and those of the correlative Asheville surface on the upthrown block is about 600 to 700 feet, which should be a measure of the throw of the Blue Ridge border fault during its reactivation (Fig. 1).

The difficulties encountered by the geomorphologist because of this approximate equivalence of interval between the three levels are obvious when one considers that downfaulted remnants of the highest or Subsummit surface on some of the outlying ranges such as the South Mountains are about equal in elevation with the upfaulted Piedmont surface (Asheville peneplain) on the Blue Ridge Upland, because the throw of the fault is equal to the original difference of elevation between the two (Fig. 5).

Such equality of elevation of two originally, separate surfaces is exceedingly misleading for the most facile analysis of the resulting topography would be to correlate them and assume that the intervening void had resulted from dissection. The plausibility of such a correlation is probably one of the weakest points of the writer's argument. However, the crest levels of similar outlying ranges in Virginia share no such concordance with strath levels in the Blue Ridge to the west of them; a fact which is readily explained by differential throw along the Blue Ridge Border fault, but difficulty explained by erosion.

Also, where the Subsummit or higher peneplain comes up to the crest of the scarp on the upthrown block there is, in most instances, a zone of broken, hilly country at the base of the scarp on the downthrown block. Thus, opposite the high surfaces of the Blowing Rock area of the upthrown block, the complementary mass of the Brushy Mountains of the downthrown block lies in close to the fault trace at the foot of the scarp. Only the narrow headwater strath of the Yadkin separates the northwestern edge of the Brushys from the base of the opposing Blue Ridge scarp, although an apparent upfaulted and dissected segment of the Piedmont surface forms the lower part of the scarp in this vicinity (Fig. 3).

Similarly, in the vicinity of Caesars Head, South Carolina, the Subsummit surface extends to the crest of the scarp in one of its steepest and narrowest parts, and below in the vicinity of Saluda, North Carolina, a narrow (apparently post-fault) valley separates the foot of the Blue Ridge scarp from an opposing mass of hills which rise rather conspicuously above the Piedmont surface. It would seem plausible to assume that these opposing masses above and below the scarp are the now dissevered and vertically displaced segments of formerly integrate remnants of the Subsummit surface.

The Subsummit surface both above and below the scarp is poorly preserved. It rarely shows large areas of undissected upland surface on the Blue Ridge Upland (*see* the Pisgah and

FIGURE 5.—DIAGRAMMATIC CROSS SECTION IN REGION OF BLUE RIDGE SCARP IN WESTERN NORTH CAROLINA

Showing inter-relationship of erosion surfaces. Upfaulted Piedmont (Asheville Peneplain) in Blue Ridge Upland is approximately the same elevation as downfaulted Subsummit surface as manifest in ridge tops of South and Brushy mountains.

Blowing Rock, North Carolina, sheets) and is dissected even more where it appears on the downthrown fault block—areas which would originally have been peripheral and, therefore, more dissected parts of the ancestral Appalachians. However, even here summit levels are accordant, and stream boulders are common on these level ridge tops.

The writer considers the straight base lines of the northwestern flanks of the outlying ranges such as the Brushy Mountains and the South Mountains to be resequent fault-line scarps developed by erosion from the old Triassic faults before the Blue Ridge border fault was reactivated. Thus the peneplaned Morganton Basin is believed to have been made by prefault erosion of the much-broken rocks of the old Triassic basin. The Morganton Basin appears to have been a graben, and this early erosion would have developed discontinuous resequent fault-line scarps on both sides of it—an ancestral Blue Ridge scarp facing eastward on the west side, and the present South Mountain scarp facing westward on the east side.

Before the Blue Ridge border fault was reactivated, the Morganton Basin probably resembled the present Asheville Basin (Asheville peneplain) of Buncombe, Henderson, and Transylvania counties in the Blue Ridge Upland of North Carolina. The writer believes the two are similar in origin and were possibly coextensive in early Tertiary time, before the Blue Ridge fault dismembered them. They are visualized as having been connected at the same level by a constricted passage similar to the present upper Yadkin Valley, which connects the Morganton Basin with the Wilkesboro Basin to the northeast on a former strath level of about 1400 feet elevation.

Southwest of the head of the Catawba strath near Old Fort, North Carolina, the later faulting, which is responsible for the present height of the Blue Ridge scarp above the Piedmont, seems to have been offset to the southeast on one or more cross faults which localize parallel valleys at right angles to the Catawba River (Pl. 1). The motion appears to have been localized at the northeast foot of Hickorynut Mountain largely in the valley of Elliot Creek, a headwater tributary of Cove Creek. Ridge tops on the southwest side of Elliot Creek consistently attain elevations averaging 2800 feet, whereas divide heights between the several small subparallel drainages between Elliot Creek and the Piedmont edge are commonly about 2200 feet. The difference between these two elevations (about 600 feet) is roughly equal to the difference in elevation between the Asheville peneplain and the Catawba strath, which suggests that the late faulting was localized in this vicinity (Fig. 1).

Cove Creek appears to occupy a longitudinal fracture parallel to the Blue Ridge border fault. It may also have been reactivated in Tertiary time. However, the principal motion, south of Old Fort, seems to have occurred on a structure which passed immediately southeast of Mike and Glaghorn mountains (Mount Mitchell, North Carolina, sheet) and Cove Mountain and the town of Saluda (Saluda, North Carolina-South Carolina, sheet). A somewhat discontinuous highland southeast of this trace has a straight-line scarp as its northwestern edge. This is thought to be similar in origin to the resequent fault-line scarp which appears to form the northwestern edge of the South and Brushy mountains farther northeast. This scarp, together with the southeastward offset, of the Blue Ridge border fault at Old Fort suggests that the reactivation followed the northwest border fault of a Triassic graben as far south as Old Fort and then moved over to the opposite side of the graben, possibly following the southeast border fault. Corroboration for this idea may be found in the fact that the Asheville peneplain, which the writer considers correlative with the upland surface of the Piedmont, approaches to the very edge of the Blue Ridge scarp in a number of places on the upthrown block opposite this outlying ridge. Since the Asheville peneplain (as well as the Subsummit) is in this area largely limited to the Asheville Basin, the Blue Ridge border fault may have been localized by the eastern edge of the basin, after which erosion on this new fault scarp cut back into the strath of the Asheville Basin itself.

The ranges to which the name "Blue Ridge" is popularly applied south of the headwaters of the French Broad River are not associated with the Blue Ridge border fault. Here, as

generally (but not without exception), south of Roanoke, Virginia, the cartographers have applied the name to the Atlantic-Gulf divide, regardless of where it is. In the area under discussion, the name "Blue Ridge" on the maps follows the essentially east-west divide between the headwaters of the French Broad and the Keowee rivers, from the vicinity of Caesars Head on the Pisgah, North Carolina-Georgia-South Carolina, sheet to the vicinity of Cashiers and Sapphire on the Cowee, North Carolina, sheet. From this last location, the "Blue Ridge" as shown on the maps turns southwestward again and becomes a broad mountainous zone of variable width, invaded from opposite sides by headwater straths of about equal elevation.

Little, if any, late faulting is believed to have taken place along the "Blue Ridge" mountain front just described. Rather the Blue Ridge Border fault is believed to have continued southwestward into South Carolina and Georgia, along the same line it seems to follow from Mike and Glaghorn mountains (Mount Mitchell, North Carolina, sheet) to Saluda (Saluda, North Carolina, sheet). Apparently the late faulting passed closely along the foot of the Blue Ridge scarp between Saluda and Pinnacle Mountain on the Pisgah, North Carolina-South Carolina-Georgia, sheet and thence, along Big Estatoe Creek on the Pickens, South Carolina, sheet; along the southeastern foot of Poor Mountain, Buzzard Roost Mountain, and Rich Mountain, and through Toccoa Falls, Ayresville, and Mount Airy, on the Walhalla, South Carolina-Georgia-North Carolina, sheet; and along the line marked by Long View, Alto, Delton, Lula, White Sulphur Springs, and Gainesville, on the Gainesville, Georgia, sheet.

The throw of the fault seems to diminish rapidly south of the North Carolina state boundary, and there are no traces of it in the topography at Gainesville, Georgia (Gainesville, Georgia, sheet).

From this gradual but consistent slope of the scarp to the southwest the existence of a Blue Ridge border fault derives major support. Within 80 miles, the scarp diminishes progressively from a local relief, above the Piedmont, of some 1000 feet (measured between the Asheville and Piedmont pene-plains) at the North Carolina boundary to extinction at Gainesville, Georgia.

Northwest of this diminishing scarp is an area which has been upthrown differentially, and a record of the uplift is preserved in the warped surface. The Asheville Peneplain slopes gradually along the fault from the 2200-foot level of the strath of the French Broad River in the Asheville Basin to the Piedmont level west of Gainesville, where the Blue Ridge border fault dies out. The upthrown block is extensively dissected in the region of the Dahlonega Plateau, but remnants of the original surface show a gradual and regular descent along the western edge of the Dahlonega Plateau, from 2200 feet in the type area of the Asheville peneplain in the French Broad Valley to the Piedmont level west of Gainesville.

LaForge (1925, p. 64) describes the Dahlonega Plateau thus:

> "Although it stands several hundred feet higher than the Atlanta Plateau [Piedmont] on the south and overlooks that plateau, the two districts are not separated by an escarpment or by a relatively steep and clearly defined slope, but by an irregular belt of broken country across which the surface descends from one to the other. Northeast of Alto, however, where the district is bounded on the southeast by the Midland Slope, [Piedmont] the two are separated by an abrupt, though rather irregular escarpment [Blue Ridge Scarp] about 500 feet high, which is one of the prominent features of that part of the State."

The well-developed strath of the north-flowing Little Tennessee River, which extends to the divide at Rabun Gap, Georgia, is a well-recognized correlative of the Asheville peneplain, and its remarkable continuity with the headwater strath of Stekoa Creek on the opposite side of the Gap corroborates the identity of the Asheville peneplain and the Dahlonega Plateau. Profiles (Fig. 2) show a gradual descent of the Asheville surface to coalescence with the Piedmont surface. They also show the relatively uniform elevation of the Piedmont surface at points equidistant from the foot of this part of the fault scarp. North of Rabun Gap, the upper profile is dual. One branch extends northward down the headwater strath of the Little Tennessee River, the other northeastward down the strath of the French Broad River. All the points south of the headwaters of the French Broad and Little Tennessee rivers were taken from the undissected headwater straths of southeastward-flowing streams along the northwestern edge of the Dahlonega Pla-

teau. To find these remnants the line of section was kept rather close to the foot of the Blue Ridge in order to avoid the dissection which followed uplift of the southeast-flowing drainage after reactivation of the Blue Ridge Border fault farther southeast.

The highest mountains of the Southern Appalachians are all north of this latitude. A zone of rough and broken topography continues to the southwest, but none of its prominences attain elevations commensurate with those of the mountains of North Carolina and northernmost Georgia. Before these last were uplifted by reactivation of the Blue Ridge border fault they probably resembled this lower, southwestward extension of the older Appalachians. In other words, this low southwestern extension of the Appalachians is still in the ancestral state, standing above the Piedmont only because of its position on the major divide.

LaForge (1925, p. 61, Fig. 3) shows the Dahlonega Plateau as extending across the southern extremity of the Blue Ridge Upland to the western boundary of the crystalline rocks where they abut the Paleozoic rocks of the Ridge and Valley Province. He shows the southern extremity of the Dahlonega Plateau as an approximately east-west line, a projection of which would intersect the Blue Ridge scarp at its terminus near Gainesville.

Lithologic and Structural Evidence of Faulting

The faults are difficult to find for they are zones of weakness along which dissection has been localized. Also the rocks are almost everywhere schistose with the planes of schistosity having the same attitude as the fault surfaces. Both dip steeply southeast and strike northeast, and the faults tend to utilize the planes of schistosity to form many obscure en echelon surfaces. However, fault surfaces are visible in section in a few cuts in the walls of fault-controlled valleys. Some of the exposures are probably of the older Triassic structures which did not share reactivation, and most of them appear to be minor parallel breaks rather than the surface of principal movement.

One such minor parallel structure is shown in the cuts of the Southern Railroad and U. S. Highway 70 about a quarter of a mile west of the railroad station in Old Fort, MacDowell County, North Carolina. Here the fault is in a massive feldspathic metasediment. The displacement on this component is probably not great, for both walls of the fault are in the same rock.

A number of small high-angle structures of small displacement in the road cut of North Carolina Highway 181, at Joy Post Office (Clear Water Beach) opposite the intersection with the Adako road, are located very closely along the trace of the Blue Ridge border fault. Mr. R. C. Heath and Mr. B. E. Warner found and sketched them (Fig. 6).

Farther northeast on Highway 181, about half a mile west of Joy Post Office, a similar structure is nearly vertical with the downthrown block on the east side.

The best exposure of the old Triassic faults is in a road cut on North Carolina Highway 268, a few hundred yards upstream from the Brown's Ford bridge over the Yadkin River, about 5 miles southwest of Wilkesboro, North Carolina. The fault here is large and seems to be one of the original Triassic structures. It seems to control the valley of the Yadkin River for 60 miles between Patterson and Siloam.

Some readers may think the rectilinear drainage pattern here ascribed to normal faulting might be caused by stratigraphic control. This is precluded because certain faults (or fault-controlled valleys) cross rocks of several types.

The Blue Ridge border fault follows the valley of the South Fork of the Catawba River from Old Fort to its point of confluence with the North Fork. Along this line Keith (1905) shows an almost straight contact between Carolina gneiss on the southeast and Henderson granite on the northwest. Northeast of the area of Keith's work the same trace marks the truncation of the younger Cambrian (?) rocks of the Linville River area against the older metamorphics of the Morganton Basin. Pratt and Lewis (1905) mapped this contact, which extends northeastward as far as Table Rock Creek (Morganton, North Carolina, sheet). These younger rocks have commonly been regarded as a fenster in the Precambrian schists and gneisses. The fault which brings the older rocks over them is a very low-angle thrust. The Cambrian quartzite dips less than 10° where it is exposed for some 18 miles in the walls

of the Linville River gorge; but as it approaches the trace of the Blue Ridge border fault it steepens in dip to 25°–30° SE. and disappears at the fault trace, suggesting downfaulting.

From Joy Post Office on North Carolina Highway 181 to the vicinity of Collettsville on North Carolina Highway 90, the Blue Ridge border fault passes through a complex of metamorphic rocks in which it is difficult to distinguish the fault trace because of lithologic similarity on both sides of it. However, between Patterson on the old North Carolina Highway 321 and the vicinity of the confluence of Elk Creek with the Yadkin River, 10 miles to the northeast, the fault seems to be marked by the contact between a granite gneiss on the southeast and a chloritic rock on the northwest. However, the actual location of the fault surface could very plausibly be in the planes of schistosity of the schist which have the same attitude as the fault.

Northeast of Elk Creek is one of the rather systematic left-handed offsets of the Blue Ridge border fault which appear occasionally throughout the length of the Blue Ridge scarp. To the northeast the younger fault diverges increasingly to the northwest from the older Triassic structure which localizes the Yadkin River, and for some distance its location, though clearly marked topographically, is obscure lithologically.

Farther northeast, in the vicinity of Dockery, Hanks Store, and Trap Hill (Wilkesboro, North Carolina, sheet), there is again a clear lithologic break along the line suggested by the topographic break. Schists on the southeast are brought into contact with granite on the northwest. For some distance to the northeast and southwest of this stretch, the fault shows the same complex metamorphic rocks on both sides. They appear to have been so thick that the throw of the fault was not sufficient to expose a different rock type on the upthrown block. However, in the Trap Hill area the fault appears to truncate the principal mass of granite of the Stone Mountain stock rather close to its original intrusive boundary on its southeast side. This area is one of the few places where the fault cuts granite, and can therefore be demonstrated by lithologic contact (Fig. 7). This is impossible where the fault surface lies in the plane of schistosity of the usual metamorphic rocks. The granite on the northwest (upthrown) side of the fault here meets the schists in a nearly straight contact for several miles. Many apophyses and pendants of the metamorphic rocks are included in the granite, suggesting proximity to an original intrusive contact. However, these all terminate along the same straight line of the fault trace, no matter how irregular their contacts with the granite may be elsewhere.

The relationship between the granite and the schist becomes more complex nearer the

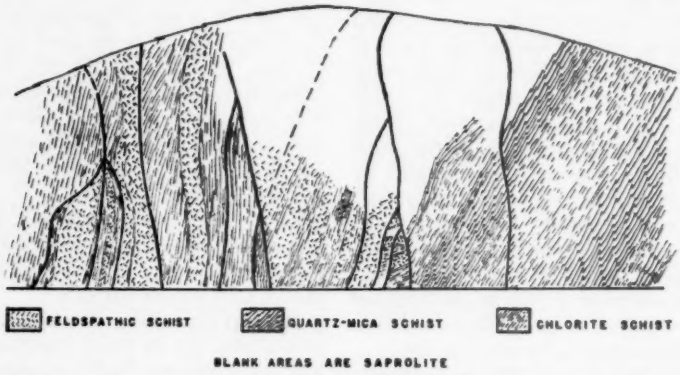


FIGURE 6.—SKETCH OF ROAD CUT ON NORTH CAROLINA HIGHWAY 181 AT CLEARWATER BEACH (JOY POST OFFICE)

Showing minor faults attendant upon the Blue Ridge border fault.

zone of original igneous contact. Thus, where the fault trace leaves the granite mass at each end, the structural relations become too fine-textured to map in this region of ubiquitous saprolite cover, sparse float, and no outcrop. The closely spaced pendants and apophyses of schist in the granite of the upthrown block cannot be distinguished from the complementary dikes of granite in the schist of the downthrown block. However, the writer considers the evidence sufficient to make a fair case for a normal-fault contact: The straight-line contact transecting several masses of schist and granite can be produced only by a fault; a fault with such a straight trace would probably be steep-angled and, therefore, more plausibly normal; the granite on the west is truncated by the fault, which suggests that the downthrown block is on the east, if, as seems plausible, the granite mass increases in size with depth.

The granite near this straight contact contains many small inclusions of schist, which suggest that an igneous contact is near-by. Therefore, one might expect that even a fault with only 500 to 800 feet of throw should, after beveling, expose host rock on the downthrown block and granite on the upthrown block, despite the fact that granite masses are normally considered to extend to great depths.

The writer has made no systematic attempt to delineate on the ground the many older Triassic faults which are suggested by the aerial photographs and topographic maps of the Morganton and Wilkesboro basins (Pl. 1). However, the sharp and straight fault-line contacts between different rocks are readily manifest in many places where faults are suggested. The contact between metamorphic rocks and granite at the foot of the straight scarp which forms the northwestern edge of the Brushy Mountains seems to be a resequent fault-line scarp which, toward its southwestern end, is held up by the granite. It may be seen on the Hickory and Wilkesboro sheets of North Carolina.

Further evidence that the drainage pattern is controlled by faulting rather than stratigraphic influences is that the rocks of the area are of igneous and metamorphic types which seldom produce geometric drainage patterns. The old sediments among them have all been differentially altered and do not preserve their lithologic identity for any great distances along the strike. In certain places in Caldwell County the quartzite gives way along the strike to a

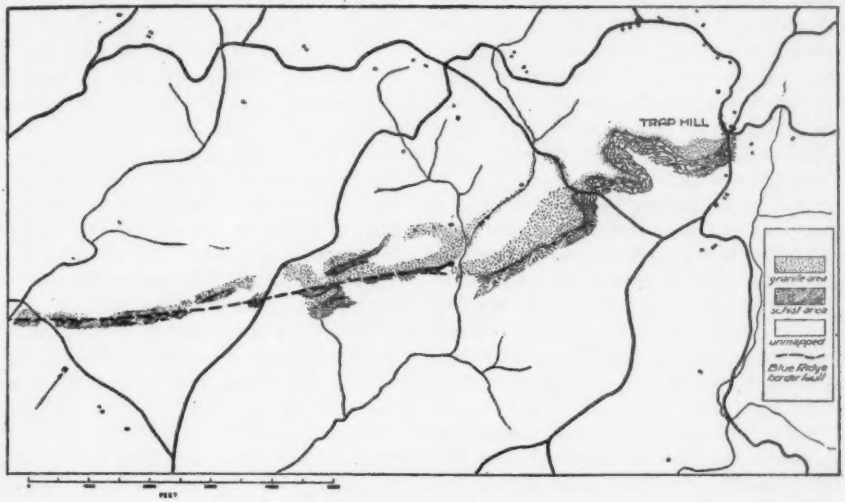


FIGURE 7.—BLUE RIDGE BORDER FAULT NEAR TRAP HILL, WILKES COUNTY, NORTH CAROLINA
For location of this map see Plate 1.

feldspathic rock, and at other places the same rock appears to have been altered to a quartz-biotite schist. Moreover, the Shady dolomite, which outcrops northwest of Marion in MacDowell County, has not been found elsewhere along the fault zone, although the subjacent Erwin quartzite reappears in several localities, and probably the more vulnerable dolomite has been altered beyond recognition. However, the dolomite may have been stripped on the upthrown block and not yet exposed on the downthrown block.

Under such lithologic conditions there is as great a differential in resistance to weathering and erosion between different parts of the same stratum as there is between different strata. It is difficult to see how such rocks, stratified as they may originally have been, could produce the persistent, parallel, lineal valleys found in this region, or a scarp which transects many rock types.

The rocks in the Triassic fault zone are not peculiar to that area but are found in the Blue Ridge scarp, in the Blue Ridge Upland west of it, and in the Piedmont east of it. One horizon is particularly significant as a key bed. A peculiar phase of the Carolina gneiss contains many large metacrysts of orthoclase which crystallize as Carlsbad twins with an average length of about 2 inches along the *c* axis, and 1–1½ inches along the *a* axis. This distinctive "stratum" has been observed at many localities throughout the fault zone and on both sides of it, from the Blue Ridge Upland in Avery and Watauga counties, North Carolina, to the middle Piedmont in Gaston County, North Carolina. Since this same rock appears both east and west of the fault zone without noticeable stratigraphic control of drainage, the rectilinear drainage within the fault zone itself should not be attributed to stratigraphic control.

The observed normal faults are free of mineralization. This possibly dates them as post-Carboniferous (Triassic or younger), for, in the older Appalachians, many of the clastic structures associated with the Appalachian revolution have been affected by the hydrothermal action which attended emplacement of the Carboniferous granites[2] of this region.

The structures in question all have the straight outcrops characteristic of high-angle normal faults. However, some of the rectilinear drainage control seems to be caused by the narrow mylonitic zones which parallel the Blue Ridge near its foot.

Possibly some support for the idea that the Blue Ridge is a fault scarp may be had from certain similarities it bears to the western borders of the closely parallel Triassic basins, which still contain recognizable sediments of the Newark Series. Thus the Blue Ridge, a fault scarp facing a downthrown block to the east, is similar to the Triassic basin of the New York-Virginia area, and the Dan River area, each with a border fault on the west side and a downthrown block east of it.

Also, topographic similarities between the border scarps of certain known Triassic basins and the Blue Ridge scarp support the conclusion that the latter was initiated in Triassic time. Thus, at the western edge of the Triassic basin in New Jersey and New York, a fault-line scarp is held up by the crystalline rocks of the Ramapo Mountains or Reading Prong. This scarp is exceptionally straight, as may be seen on the Ramapo, Greenwood Lake, Morristown, Lake Hopatcong, and Somerville sheets of New Jersey and New York. A comparison of this straight scarp with the Blue Ridge scarp as shown on Plate 1 demonstrates their similarity and suggests a genetic connection of the Blue Ridge with Triassic structures. To facilitate this comparison, the Ramapo sheet of New Jersey and New York is reproduced in Figure 8. It suggests that Triassic border faults may frequently be straight. Possibly the topographic expression of such faults may show the straightness better than the structural evidence because structural studies in inscrutable areas may mislead the observer into following minor structures where the faults ramify and the principal one is obscure. However, in the Ramapo scarp, both lithologic and topographic evidence readily locate the border fault in the same place, and its straightness is generally recognized.

[2] The term "Carboniferous" is employed here only as the name commonly used to designate the younger granites of the region. The writer does not wish to imply that they were emplaced during the Carboniferous period, but only that they appear to have been genetically connected with the Appalachian revolution.

FIGURE 8.—RAMAPO, NEW YORK–NEW JERSEY SHEET
After U.S.G.S. Showing straight scarp at northwestern edge of Triassic basin.

The presence of the long chain of recognized Triassic basins in which the sediments of the Newark Series occur supports the idea that the Blue Ridge scarp is a related structure. Principal Triassic areas in northern Virginia, as well as the Barboursville, Scottsville, Danville, and Yadkinville areas farther southwest, all lie along the same gently curved line which is roughly similar to, and congruent with, the trace of the Blue Ridge border fault.

STUDY OF FAULTS BY MULTIPLE-SURFACE ANALYSIS

In southeastern United States where deep chemical weathering is characteristic, geoogisIts have long been familiar with cracks in the saprolites made conspicuous by coatings of black, manganese oxides. Most structural geologists have regarded them as negligible. The manganese is generally recognized as super-

gene, but the writer has encountered no uniformity of opinion as to the origin of the fractures. Some geologists regard them as joints of hypogene origin, while others think they formed during weathering, either from slumping or from the expansion attendant upon hydration of the original rock-forming minerals.

In certain places most of the manganese-coated surfaces show exceptionally well preserved slickensides. At these exposures, the rock is usually completely saprolitized to a depth of many feet below the level at which the slickensided surfaces are observed, so the difficulty many geologists have had in considering the slickensides to be of tectonic origin can be understood. Offhand it would appear more plausible to assume that such well-preserved striations represent differential movement in the saprolite rather than tectonic slickensides in the surface of a faulted rock which have been perfectly preserved while the rock itself has completely decomposed.

However, since manganese oxides are probably deposited from ground water as colloids in the vicinity of the water table, tectonic structures of the original rock could be preserved by the insinuation of such material in the openings along the planes of movement while the rock was still unweathered. The colloidal manganese oxides would form delicately detailed molds of the original striations, and because of the chemical stability of the oxides, the molds would be preserved intact while erosion was reducing the surface and the zone of weathering was extending itself downward to envelope them.

More direct evidence of hypogene origin is that in certain places these slickensided surfaces pass from saprolite into fresh rock. Thus at Joy Post Office, in Burke County, North Carolina, several subparallel faults of small displacement are exposed in a road cut on North Carolina Highway 181 immediately opposite its junction with the Adako Road (Fig. 6). Several of them pass through both saprolite and fresh metamorphic rock with coatings of manganese oxides throughout.

Also, at several places along North Carolina Highway 268 in Caldwell County, slickensided, manganese-coated surfaces are truncated and overlain by undisturbed, quartz terrace gravels. It is reasonable to assume that the stream channel was operating on fresh rock when the terrace sediments were laid down; therefore the slickensided fracture must antedate weathering. If the slickensides were caused by slumping or expansion during weathering, they should have cut the overlying gravels as well as the saprolite.

The uniform structural attitude of the surfaces is most effective evidence for their hypogene origin. Over a distance of several hundred miles (Pl. 3), they appear in the same recurrent pattern, parallel to the trace of the Blue Ridge border fault. This consistency of attitude could not be explained by slump or swelling in the saprolites, for such superficial structures would be either random in orientation or parallel to the hill slope, and in neither instance would they have the consistent attitude so manifest in Plate 3.

Such slickensided surfaces, even when they have been properly regarded as tectonic, have never been considered very significant. Most of the individual surfaces have probably been displaced only inches or fractions of an inch. However, collectively they may indicate significant faulting which might otherwise be extremely obscure.

While searching for evidence of the Blue Ridge border fault in Caldwell County, North Carolina, the writer noticed many of these manganese-coated and slickensided surfaces exposed in the road cuts close to the fault trace. In the valley of Mulberry Creek southwest of Colletsville, North Carolina, and in the Yadkin Valley between Happy Valley and Wilkesboro, North Carolina, public roads follow the edge of the flood plain at the foot of the valley wall. Slickensided surfaces were noticed repeatedly in the cuts where these roads round the ends of spurs which project out toward the center of the valley floor. Assuming that the Blue Ridge border fault lay beneath the axis of these valleys, the presence of these slickensided surfaces in such salient positions suggested genetic connection with the fault.

In the hope that they might have some bearing on the problem, the orientation of a number of them was plotted on a stereographic projection.

This information was plotted on the lower

LOCATIONS FROM WHICH DATA WERE OBTAINED

1 Highway 321A near intersection with North Carolina Highway 268, near Happy Valley. This exposure on divide between Catawba and Yadkin river systems.

2 Along North Carolina Highway 268 from Patterson School to Buffalo cove Road and across the Yadkin Valley a few hundred yards downstream from the bridge across the Yadkin (first bridge below Patterson School).

3 Road bank on North Carolina Highway 268, 100 yards north east of second bridge downstream from Patterson School on Yadkin River.

4 Along North Carolina Highway 268 near Laytown Road intersection. Caldwell County, North Carolina.

5 On North Carolina Highway 268 south west of Carleton farm at Goshen, Wilkes County, North Carolina.

6 On dirt road between Trap Hill and Doughton, Wilkes County, North Carolina.

7 Same as No. 6, farther along road to the northeast.

8 Same as No. 6, farther than No. 7 along road to the northeast.

9 On U. S. Highway 21 about 1 mile north of Doughton, North Carolina, in Surrey County, North Carolina.

10 Five miles northeast of Mt. Airy, North Carolina on North Carolina Highway 104.

11 Road cut in valley wall north side of Sycamore Creek, 1 ½ miles northwest of Bowlings Springs (Critz, Virginia sheet).

12 On Virginia secondary Highway 623 between Fairy store State Park and Ferrum. 3/10 mile south of Smith River.

13 At intersection of U. S. Highway 220 and Virginia secondary Road 739 at Boone's Mill.

14 On Virginia secondary Road 684, one mile north of Maggoty Creek.

15 On Virginia secondary Road 684, ½ mile northeast of No. 14 above.

16 At intersection of Virginia Highway 116 and secondary Road 684.

17 On Virginia secondary Road 684, 3 miles northeast of No. 15 above.

18 On railroad cut of Norfolk and Western Railroad 1 ¾ miles north of Bedford, Virginia.

19 On U. S. Highway 501 at Judith Creek.

20 At junction of Virginia Highway 130 north of Elon and 1 ½ miles east of Agricola.

21 One mile west of Agricola on Virginia Highway 130.

22 At the Piney School, 2 miles west of Lowesville, Virginia on Little Piney River Road. At road intersection 200 yards east of Little Piney School.

23 200 yards south of Greenfield, Virginia on Virginia Highway 151.

24 ½ mile east of Massie's Mill on Virginia Highway 56.

25 200 yards west of intersection of U. S. Highway 250 and Virginia Highway 230 on U. S. Highway 250.

26 200 yards east of Wolftown, Virginia on Virginia Highway 230.

27 2 miles northwest of junction of Virginia Highway 16-231 and U. S. Highway 29 near Madison, Virginia.

28 ½ mile east of Boston, Virginia on Virginia Highway 522.

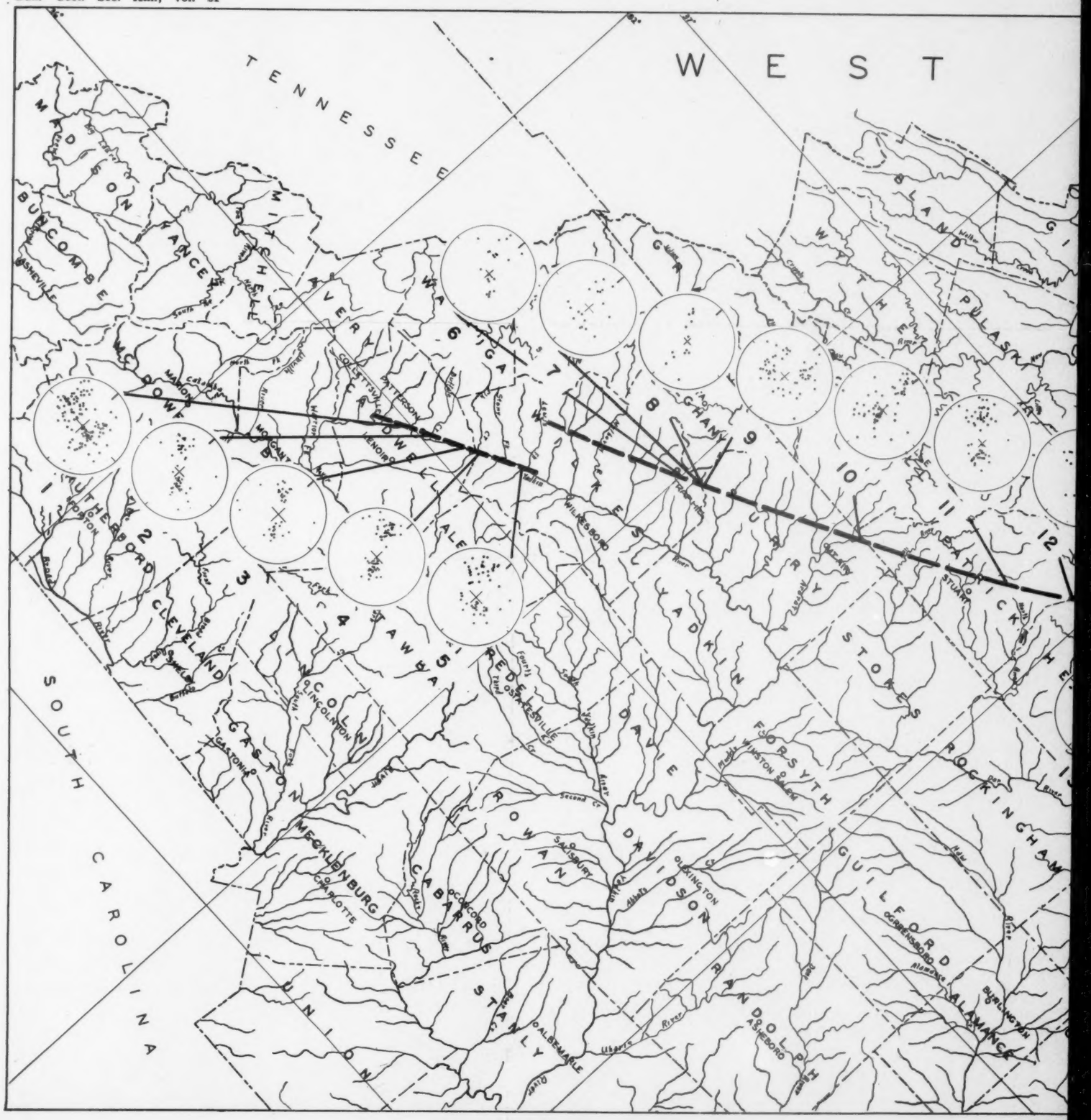
29 ½ mile west of intersection of U. S. Highway 211 and Virginia Highway 29 on U. S. Highway 211. (7 miles west of Warrenton, Virginia.)

30 1 ½ miles northwest of Dudie, Virginia on the Virginia road toward Davis.

31 ¼ mile west of crossroads on road between Lardmonte, Virginia and Middleburg, Virginia.

32 Baltimore and Ohio Railroad cut ¼ mile east of Monocacy River.

33 Maryland Highway 28 at Monocacy River on east bank.



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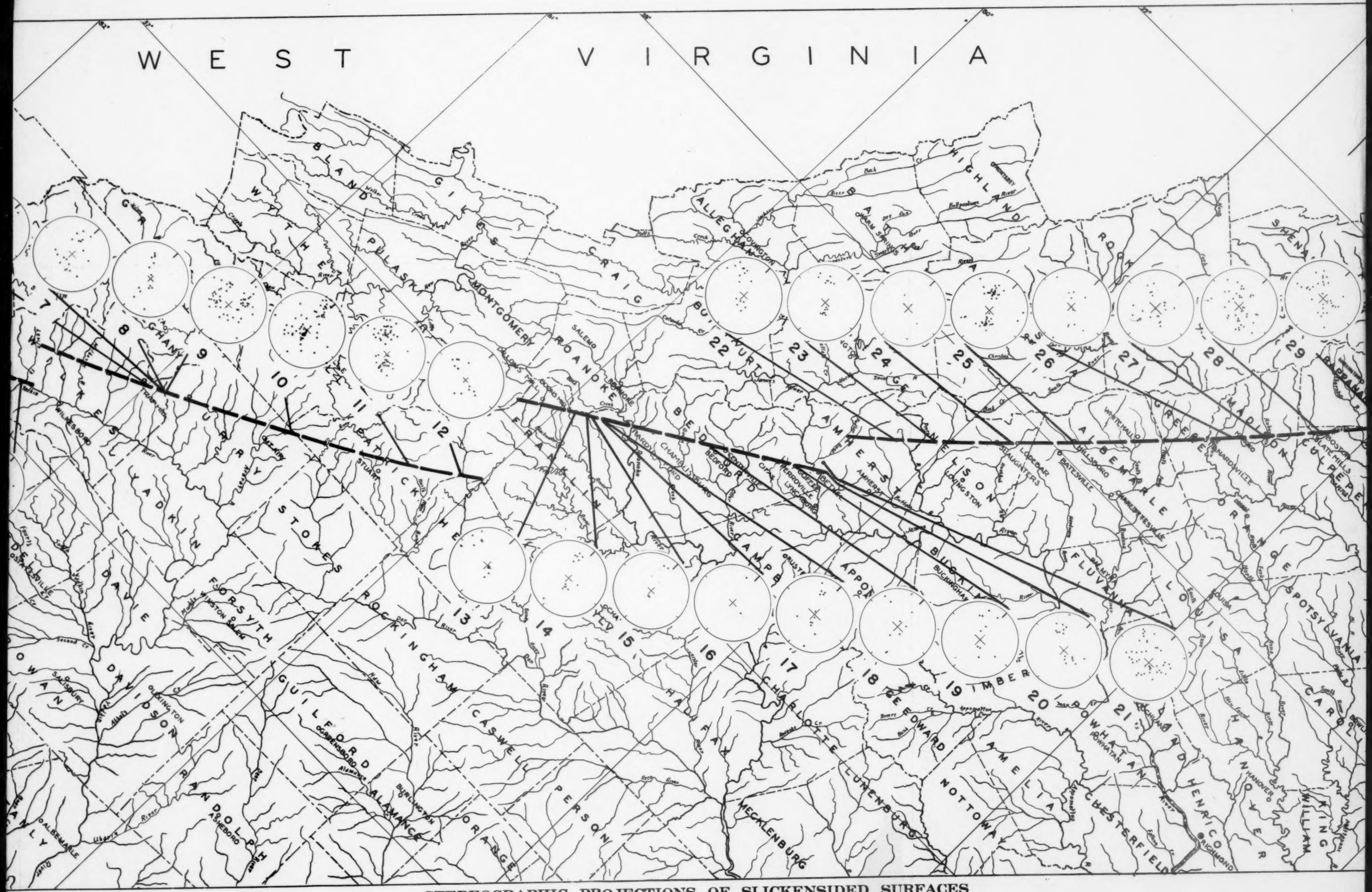
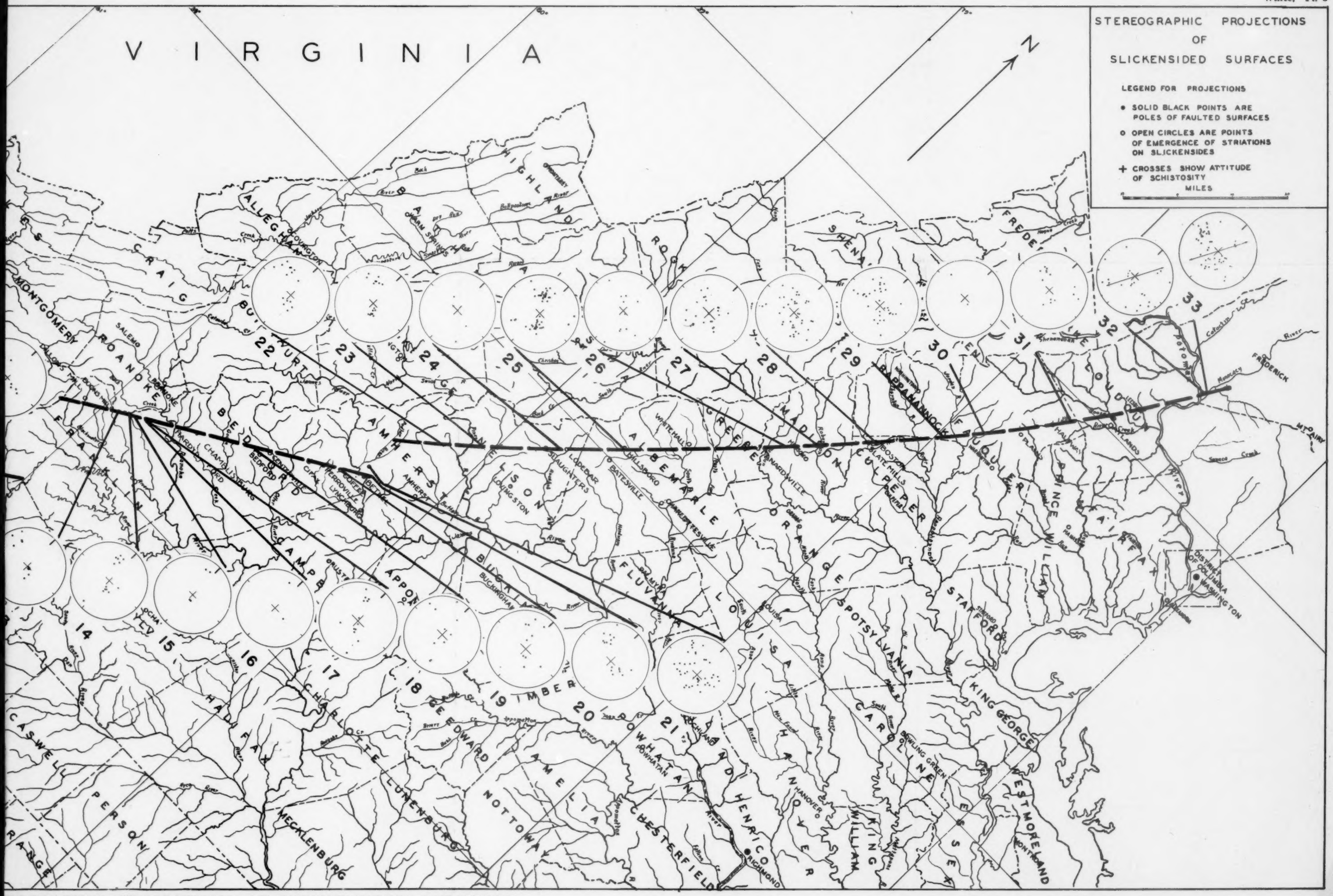


STEREOGRAPHIC PROJECTIONS OF SLICKENSIDED SURFACES



EOGRAPHIC PROJECTIONS OF SLICKENSIDED SURFACES

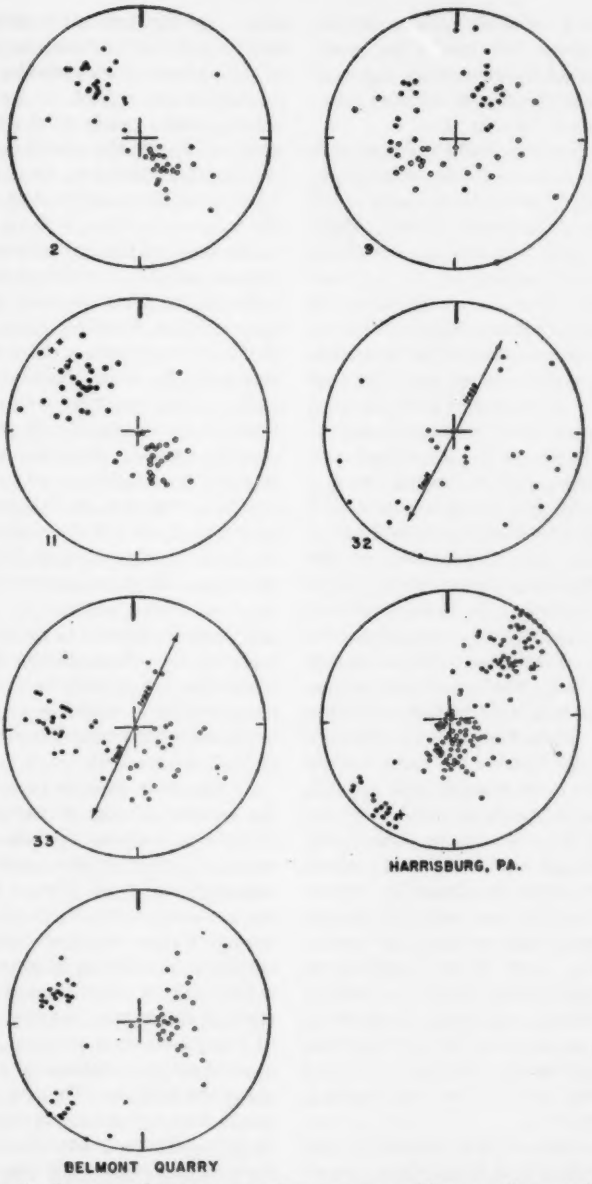


FIGURE 9.—SELECTED STEREOGRAPHIC PROJECTIONS OF MULTIPLE-SURFACE DATA
The numbers of the projections agree with those on the map shown in Plate 2.

hemisphere of the stereographic net using the poles of the surfaces and the actual points of emergence of the striations (Fig. 9, No. 2). The points center closely around the areas

suggested by the geomorphic evidence and the schistosity; the writer is convinced they represent minor parallel movements in the zone closely adjacent to the plane of principal movement of the fault.

Further data were obtained at salient points along the length of the fault trace with equally gratifying results. Observations taken at 34 locations between Caldwell County, North Carolina, and Frederick County, Maryland, produced analagous patterns.

The multiple surfaces were sought at nearly all points where well-graded highways crossed the fault trace between North Carolina Highway 181 at Joy Post Office, and Maryland Highway 28 at the Monocacy River. In most of these locations satisfactory observations were obtained, but in several instances there were no road cuts near enough to the fault trace.

Where the fault trace traverses more rugged and somewhat higher topography, the Red and Yellow Lateritic soils characteristic of the southeastern Piedmont give way locally to the Gray-Brown Podzolic soils characteristic of the Maryland and Pennsylvania country as well as the higher elevations of the southeast. The writer believes the manganese coatings are formed more readily in the Red and Yellow Lateritic soils, for in Maryland and Pennsylvania the striated surfaces are found only in fresh rock adjacent to principal fault surfaces, and little or no manganese is seen.

Such change from lateritic to podzolic soil type is abrupt and common in many places along the foot of the Blue Ridge in Virginia where the base of the scarp marks the general boundary between these two great soil provinces. Immediately south of the James River, west of Bedford, Virginia, there is a dearth of slickensided surfaces, which can probably be explained by podzolization. However, the fault trace is not very clear in this area, and it may well be that the evidence was not sought in the right places.

Projections of the multiple surfaces obtained in a few of the more critical localities are shown separately in Figure 9, and in Plate 3 they are all shown together in relation to the fault trace on the map.

Surfaces are usually inclined steeply to the southeast, and the direction of movement, as shown by the points of emergence of the striations, persistently tends to parallel the dip of the surfaces. Such attitudes are too steep to suggest any relation to the classic Appalachian thrusts which are characteristically of very low dip. On the other hand, the patterns obtained are similar to those expected from the high-angle normal faulting so common in the rocks of the Newark Series.

The close relationship between the multiple surfaces and the schistosity is shown in Figure 9, No. 11, in which the poles of the planes of schistosity are shown by crosses. The attitude of the schistosity here is characteristically parallel with the most plausible plane for the surface of a normal fault with its downthrown block on the southeast side. As King (1950) observes schistose structures throughout the length of the Blue Ridge zone consistently dip steeply to the east. Also throughout much of its length the foot of the scarp follows a zone in which steeply eastward-dipping mylonites are common. Such pre-existent structures would have the proper attitude for a later normal fault with downthrow to the east, and doubtlessly the Blue Ridge Border fault used them where they fell suitably to hand. Under such circumstances it would be extremely difficult to show by conventional means that the later faulting had occurred.

To determine whether patterns obtained in the crystalline rocks of North Carolina and Virginia were similar to those of the Triassic basins, information was sought from known faults in rocks of the Newark Series. Through the kindness of Dr. Ernst Cloos, the writer learned of three such faults exposed in a road cut on United States Highway 111 about 2 miles south of Harrisburg, Pennsylvania. A study of these faults was very gratifying (Fig. 9). Three surfaces of principal movement were exposed within a distance of about 100 yards along the highway. Their apparent displacements were not great, apparently a few tens of feet at the most, but 74 minor slickensided surfaces were observed, mostly within 100 feet of one or the other of the principal surfaces. No manganese molds were found, but the original striations were preserved in the sandstone. The pattern is consistent. The surfaces have steep dips, and usually the striations are

nearly parallel with the dip of the surface, although they consistently rake a little to the southeast because they are cross faults. The western border fault of the basin is close at hand for this cut is the westernmost exposure of Triassic rocks on the highway. Since these are minor structures subsidiary to the border fault, one would expect them to show differential motion downward and away from the border fault since they are on its downthrown block. Such a rake of the striations should not be reflected in the pattern derived from a longitudinal structure such as the Blue Ridge border fault.

The strike of these faults is quite different from that of the Blue Ridge border fault. However, except for the slight rake of the striations, the pattern presented by this projection is very similar to those obtained from the Blue Ridge border fault, and, if the projection were rotated on the page until the strike of the faults were parallel with the Blue Ridge border fault, there would be no essential difference.

These faults belong to a set of cross fractures characteristic of the structure of the Triassic in this region. Not infrequently this same transverse trend appears as a minor component of the multiple-surface data obtained from the trace of the Blue Ridge border fault where it traverses the crystalline rocks of North Carolina and Virginia. The pattern which the cross structures make on these projections is shown in Figure 9 by the projection marked Number 9 and the one marked "Belmont Quarry"; these patterns are similar to that obtained from the Harrisburg faults.

There are several offsets in the Blue Ridge scarp which usually are nearly at right angles to the trend of the scarp and the Blue Ridge border fault. They are doubtless the result of this same system of cross fractures, and they may support the idea that the Blue Ridge scarp is the result of Triassic structures, even though they may have been reactivated later.

The trace of the Blue Ridge border fault passes out of the crystalline rocks into the Triassic near Leesburg, Virginia, and crosses the Potomac River near its confluence with the Monocacy. North of the Potomac the fault is a well-recognized structure shown on the geologic maps of Frederick County, Maryland (Jonas and Stose, 1938), and of the State of Maryland (Mathews, 1933). The writer found no exposure of the principal surface here, but there is a very straight contact for several miles between the Triassic sediments to the east and the older rocks to the west, which leaves little doubt of the presence of a high-angle fault. Where Maryland Highway 28 crosses the Monocacy River, a cut shows Triassic sandstone on the east bank of the river and older rock on the west bank. These outcrops bracket the fault within a distance of little more than 100 yards. The road cut on the east bank exposes Triassic sandstone for about 200 feet along the highway, and 26 observations of slickensided surfaces were obtained from this exposure (Fig. 9, No. 33). The trace of the fault as obtained from the Frederick County geological map (Jonas and Stose, 1938) is also shown. The poles of the slickensided surfaces and points of emergence of the striations appear in close groupings on opposite sides of the fault trace as drawn on the projection. A line drawn from the center of one group to the center of the other would be about normal to the strike of the fault trace. This suggests that the attitudes of multiple surfaces are valid indices not only of the presence of faulting but also of the strike and dip of the fault.

The pattern in these known Triassic faults resembles closely the characteristic pattern obtained from observations in the crystalline rocks to the southwest in Virginia and North Carolina (Pl. 3). This lends considerable plausibility to the idea that the two structures are actually coextensive, as suggested by the topography.

After the writer had convinced himself that the method of multiple-surface analysis was useful in the analysis of faulting, he suggested its use to Dr. John W. Harrington, then a graduate student at the University of North Carolina working on a problem involving the structure of the western border of the Durham Triassic Basin. Although Harrington (1948) did not have time to obtain many slickensided surfaces from any one locality, he was able to use them advantageously. In nearly all instances they paralleled topographic or other structural features which suggested faulting in

the same location and attitude. This success of the method in a related but remote area lends credence to the findings based on its use.

At many places in the Piedmont high-angle slickensided surfaces are found in the saprolites. To the writer this suggests that Triassic

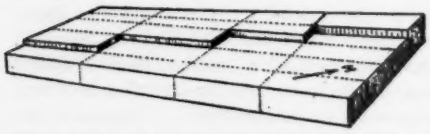


FIGURE 10.—DIAGRAMMATIC SKETCH SHOWING NATURE OF OFFSETS IN BLUE RIDGE SCARP

Dotted lines show older Triassic structures which were selectively reactivated to form Blue Ridge border fault (shown by scarp).

structures are extensively developed throughout the region, but not otherwise manifest except where they form the more conspicuous boundary faults of basins still occupied by sediments of the Newark Series. A regional study of these surfaces might cast more light on the problem of the structure and former extent of these Triassic basins, although they could easily be confused with earlier structures.

Roberts (1928) noted the connection between slickensided surfaces and Triassic faulting in Virginia. "The phenomenon of slickensides is the important mark of faulting in all the areas" (p. 73). "The Belmont fault is exposed in the Belmont trap rock quarry on the east side of Goose Creek, north of the electric railway and four miles southeast of Leesburg. This fault is marked by a great abundance of black and glistening slickenside material, which fills a fissure of a width from 15 inches up to 3½ feet" (p. 79). The writer visited the Belmont quarry and, although unable to locate Roberts' Belmont fault, obtained spectacular multiple-surface data. The diabase here is block-jointed on a regular lattice with two sets of nearly vertical joints. Practically all of them showed slickensides of nearly vertical orientation (Fig. 9, projection marked Belmont Quarry).

A similar group of surfaces (Fig. 9, No. 33) were obtained from nearly vertical joints in Triassic sandstone in the first cut east of the Monocacy River on the right of way of the Baltimore and Ohio Railroad. This location is between Maryland Highway 28 and the Potomac River. Here, as at the Highway 28 location, the fault seems to be very close to the river.

Such presence of slickensides on all near-vertical joint surfaces strongly suggests that the differential movement in rocks closely adjacent to a fault surface of principal movement utilizes as surfaces of minor movement practically all available fractures or planes of excessive weakness that are so oriented as to permit slipping. Thus, in both the Baltimore and Ohio Railroad location and the Belmont quarry location, the presence of slickensides on most of the near-vertical joint surfaces suggests the close proximity of a fault whose surface of principal movement was also close to the vertical.

In the projections of these surfaces, the strike of the multiple surfaces is not significant and is highly variable, but the direction of movement is in all instances close to vertical.

OFFSETS IN THE BLUE RIDGE SCARP

An interesting subsidiary feature of the Blue Ridge scarp and its engendering border fault is the more or less systematic series of offsets throughout its length. These offsets are apparently caused by transverse faults. Each causes a left-handed displacement of the scarp, although the direction of motion on them seems always to be nearly vertical. The downthrown block in each instance seems to be on the northeast.

Beginning at the southwestern end of the scarp the first offset is in the vicinity of Old Fort, North Carolina (Mount Mitchell, North Carolina-Tennessee sheet). It sets the Blue Ridge scarp off to the left about 10 miles. This particular offset is described above. Northeastward along the scarp, others are found near the lower course of Stony Creek (Wilkesboro, North Carolina, sheet), where the displacement is about 2 miles; near Callaway and Junta (Christiansburg, Virginia-West Virginia, sheet), where the displacement is about 3 miles; and at the James River (Buena Vista, Virginia, sheet), where the displacement is about 8 miles. These can all be seen on Plate 3, and the Stony Creek offset can also be seen on Plate 1.

Such a series of offsets might seem to indicate transcurrent faulting, but actually there

is little to suggest that the displacement on these faults was horizontal. The base line of the scarp is offset very sharply along what seem to be ancestral cross fractures. In each instance there is higher ground on the southwestern side of the cross fracture, and the higher elevations usually terminate abruptly along it (Fig. 10). The topographic details of the offset in the scarp between Marion and Old Fort in North Carolina have been described elsewhere in this paper. Similar situations prevail at the site of the Stony Creek and Callands offsets. The situation is rather confused, but similar in the vicinity of the James River. The offsets north of the Potomac conform to the same pattern but are not as diagnostic because the scarp has been weathered back from the fault trace which is in the softer Triassic rocks to the east. The offsets show here only because the older transverse structures have displaced the narrow zone of resistant older rocks to the west, and the softer sediments have been eroded from around them.

The absence in the Blue Ridge scarp of the overlap characteristic of en echelon, transcurrent faulting, and the presence of the cross fractures at the points of offset, coupled with the fact that the base line of the scarp follows along the offsetting fractures, suggests that the movement of the Blue Ridge border fault was dominantly in the vertical dimension. It also suggests that the strike of the fracture needed for relief of the stress which produced the reactivated faulting did not quite parallel the strike of the pre-existent Triassic breaks, and that the reactivated motion would therefore follow one of the pre-existent breaks for a considerable distance and then jump across to a parallel structure, utilizing some fortuitously located cross fracture.

The offsets in the Blue Ridge are topographic, not lithologic; the scarp itself is offset, but the rocks are not displaced laterally. This is significant in two ways: (1) it obviates the possibility that the offsets are tears connected with a low-angle thrust, and, (2) it militates further against the old idea that the Blue Ridge scarp is purely an erosional feature, for the development of such sharply rectilinear landforms could hardly be of purely erosional derivation if they are not associated with coextensive offsets in the rocks from which erosion etched them.

The only remaining explanation is that they are steep-angled normal faults of nearly vertical displacement—an idea which is borne out by the presence of so many points in the projections (Fig. 9, No. 9) which suggest near-vertical movement on cross fractures.

At the points of offset, it is sometimes possible to perceive the longitudinal, ancestral fracture extending northeastward or southwestward beyond the point at which it was abandoned by the younger faulting. It is usually an obscure trace, manifest only by drainage control or a low fault-line scarp. At the Stony Creek offset in Wilkes County, North Carolina, the ancestral structure extends northeast along the Yadkin River while the scarp is offset to the northwest along the cross fault (Pl. 1).

Many minor structures parallel these offsets but show no evidence of late movement. Many of them in the Morganton Basin are shown by their control of minor drainage.

North of the Potomac, the Blue Ridge border fault is topographically obscure. Triassic sediments on the upthrown block have been reduced to the general level of the downthrown block or even lower by Harrisburg and later peneplanation, and the Blue Ridge, composed of resistant crystalline rocks, is remote from the fault trace. Offsets of this unreactivated type are seen in the plan of the Blue Ridge here. These faults are not consistent in the direction of offset, and there is no reason to believe they are genetically connected with the Blue Ridge border fault. However, their occurrence along the western border of the Triassic rocks from Virginia to New Jersey supports the idea that the offsets in the Blue Ridge scarp farther south are the result of later utilization of similar structures; their presence should indicate that a zone of Triassic structures existed in that region also even though no sediments of the Newark Series remain.

Occurrence of these more southerly offsets in a fault trace at the foot of a straight scarp offsetting both trace and scarp where rocks of essentially equal resistance appear on both sides of the trace not only indicates the presence of Triassic structures, but that these Triassic

structures have been reactivated in the manner suggested by Figure 10.

The presence of these cross faults throughout the Triassic basins of the eastern United States distributed in parallel orientation throughout the Piedmont, there is only one minor occurrence northwest of the Blue Ridge border fault.

Recent work of Reineman (1948) in the

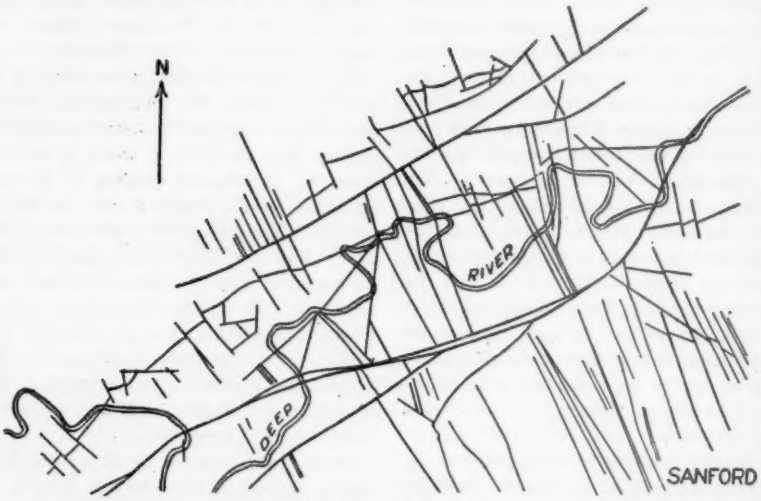


FIGURE 11.—FAULT PATTERN IN DEEP RIVER TRIASSIC COAL BASIN OF NORTH CAROLINA
After Reinemund. Many of these structures are occupied by dikes.

's shown on many maps. They may be seen along the western border of the Triassic sediments on the geologic map of the Raritan, New Jersey, Folio (Bayley, Salisbury, and Kümmel, 1914); on the Fairfield, Pennsylvania, Folio (Stose and Bascom, 1929); on the geologic map of Pennsylvania (Stose and Ljungstedt, 1931); on the geologic map of the Warrenton, Virginia, Quadrangle (Furcron, 1939); on the geologic map of the James River Iron and Marble Belt, Virginia (Furcron, 1935); on the geologic map of Frederick County, Maryland (Jonas and Stose, 1938); and on the geologic map of Virginia (Stose, 1928).

In the Triassic basins of the South, the cross faults seem to be more prominently and systematically developed. Thus in the Durham Triassic basin of North Carolina, Harrington (1948) noted many closely spaced subparallel cross faults. The same trend is shown on the geologic map of Georgia (Stose and Smith, 1939) by its localization of Triassic dikes. Although these dikes appear rather generally Deep River Triassic Basin of North Carolina shows a strongly recurrent pattern of longitudinal and cross faults (Fig. 11). Comparison of this map with aerial photographs of the Morganton and Wilkesboro basins shows great similarity between the fault pattern on the Deep River map and the drainage pattern of the Morganton Basin, strongly suggesting a Triassic origin for the structures controlling the latter, since the faults of the Deep River Basin occur in recognized Newark sediments.

The possibility that the Blue Ridge scarp is the result not of reactivated Triassic faulting but of the stripping of easily eroded Triassic sediments from the face of an old Triassic border fault appears to be precluded on several bases.

(1) The offsets in the Blue Ridge scarp where the Blue Ridge border fault traverses crystalline rocks are all systematically left-handed for several hundred miles along the scarp, whereas the cross faults in the Triassic sediments and the offsets in the borders of the sediment-filled

basins are either right- or left-handed. This may be verified on the several geologic maps listed. If the scarp were the result of the stripping of Triassic sediments from the surface of a border fault, the offsets in it should be randomly left- or right-handed as they are elsewhere in unreactivated border faults of the Newark basins.

(2) If the Blue Ridge scarp were the result of such stripping of sediments from its face, it would seem improbable that the scarp should still be preserved with such a straight base line and a peneplaned surface at its foot; without that peneplain having beveled at least a few small remnants of the down faulted sediments in the bottom of the basin opposite the place of maximum development of the scarp. Considering the complex nework of faults characteristic of the Triassic basins it would seem necessary that the floor on which the Triassic sediments rest should be greatly differential in elevation with certain parts more deeply downfaulted than others. Therefore, if the present Piedmont surface at the foot of the scarp had been made by etching out the vulnerable Triassic sediments, it should either be an irregular surface determined by such irregularities of the stripped basement, or it should be a peneplained surface like the present Piedmont but beveling many deeply downfaulted remnants of the Triassic sediments. But no such remnants of Triassic sediments appear where they should most plausibly be expected by such a hypothesis—opposite the youngest, steepest, and highest part of the scarp in the Morganton and Wilkesboro Basins of North Carolina.

Remnants of the Triassic sediments are preserved reasonably close to the foot of the scarp only in northern Virginia where it is deeply eroded and the greater number of the spurs have been eroded back from the fault trace.

However, if the Blue Ridge scarp is a reactivated fault scarp, the old Triassic basin could have been eroded and peneplaned before reactivation to depths considerably below the bottom of the sediments, so that later faulting, in reactivating some of the Triassic structures in the basement, should be enough to show the influence of Triassic structural trends without displaying a single remnant of Triassic sediment. Such greater depths of erosion are what one expects in this perennially high part of the southern Appalachians.

(3) The zone of Triassic faulting in North Carolina where the scarp is best developed is limited to the Morganton and Wilkesboro basins (Pl. 1), and the resistant crystalline rocks of the Piedmont would not readily have been peneplaned on the east side of the Brushy and South mountains in the same short time required to strip soft Triassic sediments from their western sides. The headwater tributaries would have stripped such sediments long before the lower Piedmont had been more than trenched by its streams. Moreover, if the stripping had taken place sufficiently long ago to allow later peneplanation of the crystalline rocks of the Piedmont east of the Triassic, the Blue Ridge should be complementarily reduced and cut back, not a steep and straight scarp.

It might also be well to consider the possibility that the Blue Ridge Front is a fault-line scarp independent of any ancestral influence of stripped Triassic sediments. A fault-line scarp is the expression of a difference in rock resistance on opposite sides of a fault trace, and in a complex of crystalline rocks such as those presented by the Blue Ridge front it would be implausible to expect that the more resistant rock should always chance to be on the same side of the fault throughout a distance of several hundred miles. The type of rock found on opposite sides of the trace of the Blue Ridge border fault changes many times throughout the length of the fault, but the scarp is consistently on the northwest side.

Moreover, a fault-line scarp in such rocks should not only alternate its appearance on opposite sides of the fault trace, but the several segments of the scarp on each side of the fault should be separated by wide gaps where the more vulnerable rocks had been reduced. Such discontinuous scarps are exemplified by the northwestern flanks of outlying ranges like the Brushy and South Mountains. The broad 10- to 20-mile gaps between them are occupied by the valleys of major streams. No such gaps are found in the Blue Ridge scarp. There are very few openings through it, and they are either the narrow steeply incised water gaps of strong antecedent streams such as the Potomac and James or a few equally narrow wind gaps of

defeated streams. However, a number of broad strath terraces can be found in the crest of the scarp where parts of the Asheville surface come out to its edge. Before reactivation of the fault these were probably extensions of the Piedmont surface, and the highlands between them would have been the northwestern components of a discontinuous fault-line scarp ancestral to, and still surmounting the present Blue Ridge fault scarp. The opposing southeastern components of the ancestral scarp originally developed where the more resistant rock happened to appear on the southeastern side of the fault trace are still recognizable as some of those places where the highlands rising above the Piedmont level face the Blue Ridge Front closely against the fault trace. However, mylonitization and multiform Triassic faulting apparently so weakened a zone along the foot of the scarp that it was cut out during the development of the Piedmont peneplain leaving discontinuous fault-line scarps facing each other across broad open straths such as the Morganton and Wilkesboro basins. Because of this zone of weakness, and the fact that the ancestral Appalachians have long been a divide area, the old fault-line scarp no doubt had more highland remnants on the northwest or Blue Ridge side of the fault trace than on the southeast or Piedmont side.

Another fact which seems to support the idea that the scarp is a fault, rather than fault-line, feature is that the highest mountains of the Appalachians are found on the upthrown block in North Carolina where the throw was greatest and the scarp seems to be the youngest. As the scarp dwindles southwestward from the North Carolina-South Carolina boundary, the elevations of the mountains on the upthrown block also fall off in the same direction. This is not conclusive evidence of faulting, but it does suggest that part of the extreme elevation of such mountains as Mitchell, Grandfather, and the Smokies is the result of upfaulting which was not shared by the mountains of Georgia and the Talladega Hills to the southwest. Again, the convergence of the Piedmont surface with the Asheville Peneplain (Dahlonega Plateau) at the southwestern end of the Blue Ridge scarp (Fig. 2) opposes the idea that the Blue Ridge Front is a fault-line scarp as strongly as it opposes Davis' idea of two simultaneously developed peneplains. The Piedmont surface below the scarp is cut on crystalline rocks which have resistance to degradation commensurate with that of the mountains above the scarp; and the difficulties of cutting the Piedmont down to its low relief and low elevation while preserving the Blue Ridge Upland at its higher elevation are essentially the same as the difficulties found in Davis' hypothesis.

Opposing Opinion

Wright (1927) lists several criteria by which he seeks to test the validity of the fault theory of origin for the Blue Ridge scarp. His application of these criteria led him to conclude that faulting was not present. The writer believes that Wright's criteria are, in general, valid, but that his application of them is largely invalid. His criteria and his findings are discussed in the order in which he presents them:

1. "Simple base line." Wright states that a normal fault scarp should have a simple base line, either straight or curved. After considerable examination of the Blue Ridge scarp in North Carolina and southern Virginia, he found no such simple base line and concludes that it is not present. To demonstrate this conclusion, he presents a figure showing only the 1500-foot contour line which runs along the face of the scarp near its base. A line joining the points where this single contour line rounds the ends of the principal spurs is fairly straight, but because it is not quite straight Wright considers its small irregularity proof that there is no straight base line.

There is no reason why the fault trace should maintain a uniform elevation throughout its length. The writer would like to refer to his description of the strikingly straight base line which appears at the foot of the spurs of the scarp between Old Fort in MacDowell County, North Carolina, and the vicinity of Mount Airy, in Surry County. This straight base line is shown decisively by the topographic maps of Plate 1 and the topographic sketch of Plate 2 which was constructed mechanically by foreshortening and lifting contours and, therefore, does not reflect personal interpretation. The

straightness of the base line may also be seen somewhat less dramatically, throughout the length of the scarp in Virginia, but one should recall that, when a fault scarp has been extensively eroded, some of its spurs may be cut down to the level of the downthrown block. Very little of this has occurred in the Blue Ridge scarp in North Carolina where practically all of the spurs come out to the fault trace.

2. "Base line independent of rock structure." Although Wright found no straight or simple base line, he admits that the foot of the scarp does not follow any particular stratigraphic horizon and that it seems to be independent of local structures. This is one of the two criteria which he does not find opposed to the fault theory. However, the writer would like to recall the reader's attention to the above enumeration of the several rock types traversed by the Blue Ridge border fault.

3. "Two unequal slopes." Wright observes that block mountains usually have two unequal slopes, of which the fault scarp is the steeper. He finds this criterion, like number 2, in general satisfied by the topography of the Blue Ridge scarp. But he does not consider either of these as good criteria as the other five for which he finds no evidence.

4. "Short, parallel consequent streams flowing down the scarp." Wright states that a fault scarp should be dissected by many parallel consequent streams and that the Blue Ridge scarp fails to fulfill this requisite because its drainage is irregular in direction. He is in some measure correct in this observation although the consequents are present and in many instances nearly parallel. However, this criterion cannot be applied strictly to the problem of the Blue Ridge scarp, for the consequent drainage of the scarp would have been developed by headward erosion after faulting. The rocks to be dissected would have been metamorphics of great lithologic and structural complexity with their directions of weakness oriented at odd angles with the direction of the initial consequent streams on the newly upthrown scarp. Such rocks would have been highly differential in resistance to erosion. Therefore, in working headward the new consequent streams would be largely controlled by the structure and lithologic character of the rocks. They would finger their way into the weaker zones and take on from a very early stage the character of subsequent or adjusted streams. Furthermore, many of the streams would have been part of the pre-fault Atlantic drainage system, such as the Roanoke, Dan, Linville, and Green rivers. Such streams would not have been new consequents, but rejuvenated pre-existent streams. They would have entrenched themselves in their former channels, thus maintaining courses quite independent of the initial slope of the fault scarp.

The writer concludes that highly parallel consequents are characteristic of fault scarps only when the scarps are very young or when they truncate horizontal strata or homogeneous rock. Perhaps it is because so many of the classic fault scarps have appeared in such rocks that the idea of parallel consequents has been so frequently presented as a criterion of faulting.

5. "A series of short parallel spurs dissected out of the scarp and terminating approximately in a line marking the former position of the fault surface." Wright describes the Blue Ridge spurs as "sprawling" and notes that they show very little parallelism throughout the 150 miles of scarp he studied. This observation is but a variorum statement of his fourth criterion, and the writer's criticism is the same; if the streams flowing down the scarp are not parallel because of their adjustment to the weaker rocks, so likewise the spurs between the streams may fall short of parallelism without detriment to the fault theory.

In reference to the statement that the spurs should terminate along the fault trace, Wright like Davis (1909) whom he quotes, was unable to see the linear relationship of the terminations of the spurs which have been discussed at length above and are so clearly evident on Plates 1 and 2.

Wright also discusses the problem of explaining the outlying hills at the foot of the scarp (Brushy Mountains, South Mountains, etc.). He admits they could be pre-fault prominences on the downthrown block, as the writer has suggested, but he considers this very dubious because he can find no extension of them to the southwest along their axial trends on the Blue Ridge Upland (the upthrown fault

block). This difficulty may be removed by the writer's theory that the wide Piedmont-level straths, such as the Morganton Basin, which separate these outliers from the Blue Ridge scarp, are pre-fault straths developed on an old, much-broken Triassic fault trough or graben. Therefore, the outliers would have been originally, as now, discrete ranges on the opposite side of the basins from the Blue Ridge.

6. "Triangular facets." Wright notes that faceted spurs are a characteristic attribute of young fault scarps and considers that their absence from the Blue Ridge scarp is evidence against the fault theory. Such facets are uneroded remnants of the fault surface, and the writer believes that the Blue Ridge scarp has been eroded to an extent which has removed all traces of the original surface. This is shown by the wide straths cut into it by the dissecting drainage, and by the fact that the base line or fault trace is largely delineated by the low-lying extremities of intricately dissected spurs. Dissection of the Blue Ridge scarp has progressed so far that virtually all remnants of the original surface have been destroyed; therefore few if any facets should be found.

7. "Stratigraphic displacement." The rocks traversed by the Blue Ridge fault are nearly all metamorphosed. Metasomatism has changed their lithologic character; closed folding, faulting, and mylonitization have complicated their structure; and most particularly, the attitude of schistosity parallels the surface of the Blue Ridge border fault. It is thus extremely difficult to determine stratigraphic displacement.

In the conclusion of his paper Wright expresses further doubt of the validity of the fault theory because fault-block mountains usually have a gentle back slope on which consequent drainage should develop subparallel streams. As stated above, new, but not necessarily parallel, streams should develop on the fault scarp, for this is a new surface to a large extent free from the influence of pre-fault drainage. On the back slope, however, no new surface has been exposed, and there is no reason for the creation of a new consequent drainage. The back slope results from uplift and tilting of an old surface, not the creation of a new one. The uplift of an old surface does not produce new consequent streams, but rather induces the old drainage to intrench.

Description of the Blue Ridge North of Roanoke

North of Roanoke, Virginia, the Blue Ridge is not a scarp at the edge of a broad upland but a ridge, as its name (which probably originated there and was later carried south to apply to the scarp) implies. However, it is not a narrow hogback, but in many places shows definite though narrow remnants of former peneplains on its summit. It parallels the western edge of the crystalline rocks, but remains almost wholly within them. West of it lie the younger, unmetamorphosed, and generally less-resistant, Paleozoic sedimentary rocks which have been extensively dissected. The tops of the most resistant ridges in the Paleozoic area are roughly commensurate in elevation with the higher peneplain remnants on the crest of the adjacent parts of the Blue Ridge.

If the northern section of the Blue Ridge is the result of faulting, the fault should be found at the eastern foot of the ridge and would seem to have been localized by the contact between the Paleozoics and the crystallines which are apparently brought together by a thrust which antedates Triassic faulting.

By paralleling this lithologic contact northward, the Blue Ridge border fault would have moved increasingly farther east of the Atlantic-Gulf divide, leaving progressively larger drainage areas of the east-flowing streams on its upthrown block in the softer Paleozoic rocks.

The writer believes that the faulting began in the northeast and progressed southwestward. Thus the northeastern reaches of the scarp would be older than the southwesterly ones. The scarp has a much younger appearance in its more southwesterly reaches than it does farther to the northeast, and in general its topographic age appears to increase northeastward. In North Carolina it is more precipitous than in northern Virginia; the crest line is much closer to the fault trace, and practically all the spurs extend down to the fault trace, but as one goes northeastward along the scarp, the crest line tends to fall farther away to the

northwest of the fault trace, and an increasing number of the spurs have retreated by reduction to the Piedmont level so that they no longer terminate at the fault trace but at different distances behind it. Still farther northeast in northern Virginia and Maryland where the fault passes into the less resistant sedimentary rocks of the Triassic and Paleozoic, the scarp is represented only by the diminishing residuum of the upthrown surface preserved on the increasingly narrow outcrop of the crystalline rocks which happens to fall progressively farther northwest of the fault. In Maryland and Pennsylvania most of the upthrown block, which brought up the less resistant rocks of the Paleozoic and Triassic, has here been reduced to the several levels of the post-fault erosion cycles (Harrisburg and younger surfaces).

Because of its passage through these weaker rocks and its earlier development, the scarp is topographically much older near its northeastern extremity, and there it bears little resemblance to its more southwesterly reaches in southern Virginia and North Carolina, where the more resistant crystalline rocks are found on both sides of the fault.

It is of great importance to juxtapose the influences of these two factors in appraising the idea that the scarp is the product of the same dynamic and erosional events throughout its entire length, no matter how different its several parts may be in their present status of reduction.

It may be difficult for the reader to allow this analysis when he considers that the crest line of the scarp is less than a mile from the fault trace at several points in North Carolina, whereas it seems to have retreated tens of miles across the sedimentary rocks of Pennsylvania. However, this discrepancy may not seem so great when one compares the gorges of the North Carolina section of the scarp with the post-fault dissection achieved by the streams which drain the narrow residuum of crystalline rock which forms the Blue Ridge in Maryland and Pennsylvania. There, as in the southwestern reaches of the scarp, dissection has been slow and is still in the stage of youth. Such streams as Conewago and Marsh creeks on the Fairfield, Pennsylvania, sheet still preserve young gorges little different from those in the Blue Ridge scarp of North Carolina and southern Virginia, despite the fact that the surrounding area of less resistant sedimentary rock has been generally reduced to the Harrisburg and younger post-fault erosion surfaces.

However, despite the obvious reasons for the more rapid development of topographic age in the northern reaches of the scarp, some readers may feel that the discrepancy in erosional status if too great to be thus explained even when one postulates that the faulting began in the northeast and progressed slowly southwestward. They may feel that the difference in present status of the two extremities is so great that its explanation would demand a progressive extension of faulting so slow as to be incredible. If so, it may be pertinent to compare the Blue Ridge with the Hawaiian Archipelago. There the islands appear to have been made by successive igneous extrusions along fractures in the ocean floor. Loci of these extrusives seem to have extended progressively southeast over a very long time. This southeastward migration of vulcanism could be an index to a simultaneous southeastward extension of the fractures which made it possible. The present high islands are all at or near the southeastward end of the fractures and are apparently much younger than the low reefs and atolls of the northwestern part of the archipelago which seem to have been made by older extrusions when the fractures were active in that locality. These older islands apparently have been truncated by erosion, and the apparent differential in erosional status between them and the increasingly high islands to the southeast is much greater than that between the opposite ends of the Blue Ridge scarp, although it is admitted that the erosional processes as well as the tetonics are not necessarily similar.

Possibly some support for the idea of differential age in the opposite ends of the Blue Ridge border fault as well as support for the actual existence of the fault may be found in the seismic history of the region. Heck (1929) writes:

"Pennsylvania and West Virginia appear to be peculiarly free from earthquakes in spite of their mountainous formation.

"Virginia has had a considerable amount of earthquake activity though little of great severity. "The Appalachian region from North Carolina to Alabama has had a fair amount of severe shocks."

Again Heck (1934) writes:

"There is little indication of extension of activity along the axis of the Appalachians in Alabama beyond their point of disappearance beneath the surface."

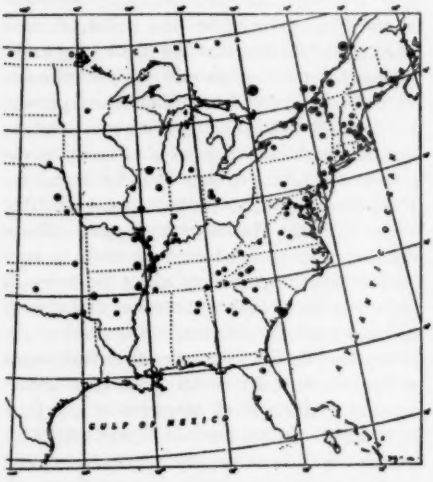


FIGURE 12.—DESTRUCTIVE AND NEAR-DESTRUCTIVE EARTHQUAKES OF THE EASTERN UNITED STATES THROUGH 1939
After Bodle (1939).

Figure 12 shows the loci of recorded earthquakes of destructive or near destructive intensity. Their concentration along the Blue Ridge axis suggests that it is still a zone of minor activity. Heck notes that the more severe shocks have been largely concentrated at the southern end of the zone. This is of interest in connection with the idea that the Blue Ridge border fault seems younger near its southern end.

Heck suggests that few earthquakes have been recorded south of the Gainesville termination of the Blue Ridge border fault (Fig. 12).

Still clearer evidence of late faulting along the foot of the Blue Ridge is obtained from two small normal faults which may be seen in a road cut on the north side of U. S. Highway 250 near Hillsboro in Albemarle County, Virginia. These are especially significant because they displace high-level fluvial gravels of probable pliocene age. They are about 20 feet apart. The western one displaces the gravels about 4 feet and the eastern one displaces them about 1 foot. Both have nearly vertical surfaces and are down-thrown to the west. They closely resemble the small scarps thrown up during earthquakes along the bases of active fault blocks such as the Sierra Nevada. The fact that they are down-thrown to the west does not dissociate them from the Blue Ridge border fault for such minor attendant movements are frequently reversed in throw from the major structure. Their location is very closely in line with the projected location of the Blue Ridge border fault.

The Blue Ridge in northern Virginia is held up largely by the resistant Catoctin greenstone and the hypersthene granodiorite. These rocks probably preserved an ancestral Blue Ridge even against the extreme degradation of the Schooley cycle. However, the writer believes this ancestral pre-fault Blue Ridge was a chain of segregate hills with occasional broad, low gaps where Schooley-level straths passed between then. The geologic map of Virginia (Stose, 1928) shows that the Catoctin greenstone occurs not only in the long, continuous outcrop which forms the backbone of the Blue Ridge between the James and Potomac rivers, but also in a very similar zone which parallels the Blue Ridge in an equally long, narrow, and persistent outcrop 5 to 15 miles to the southeast. This more easterly zone diverges from the main mass of the Blue Ridge, north of the Potomac to form Catoctin Mountain. It crosses the Blue Ridge fault at the southern extremity of Catoctin Mountain and southwest of that point localizes a long, loosely associated chain of outlying hills parallel with and a short distance southeast of the Blue Ridge fault trace. These outlying hills of greenstone extend to the James River or as far south as the greenstones of the Blue Ridge crest line.

Two such closely parallel outcrops of the same resistant formation would hardly be so different in topographic manisfestation just because of differential erosion. Since the western outcrop stands as a high, precipitous, and nearly unbroken ridge throughout its entire length, it

would hardly seem plausible that the closely adjacent parallel outcrop should be reduced to a broken line of sparsely distributed monadnocks of minor relief. Some factor such as faulting seems necessary to explain the discrepancy. The writer believes the present line of monadnocklike hills which marks the eastern zone of greenstone on the downthrown block is a good counterpart of the ancestral Blue Ridge before faulting elevated it.

For other reasons also it is evident that the resistance of the greenstone is not the sole reason for the elevation of the Blue Ridge. Spectacular and persistent sections of the Blue Ridge in north and central Virginia are held up by other rocks such as the hypersthene granodiorite and Cambrian quartzites. Furthermore, the Blue Ridge here is a narrower, but none the less valid continuation of the more southerly sections of the province in southern Virginia and North Carolina, where many kinds of metamorphic rocks enter into its composition; and farther north in Maryland and Pennsylvania, although the Blue Ridge continues as an unbroken topographic feature, other rocks are the principal ridge makers. The greenstones persist across Maryland but die out near the Maryland-Pennsylvania boundary save for a very few isolated and unimportant remnants. The ridge in the Pennsylvania section is held up by aporhyolite and Cambrian quartzite.

Moreover, the terminations of spurs along the fault trace are independent of both the Catoctin greenstone and the hypersthene granodiorite. Despite the fact that they fall along a markedly straight or smoothly and slightly curved line, they are held up by a variety of other rocks in addition to those two; this strongly suggests faulting.

The higher elevations in the Blue Ridge do not persist north of Manassas Gap in northern Virginia. This rather abrupt diminution of crest elevations is approximately coincidental with the northern extremity of the hypersthene granodiorite, but the Catoctin greenstone continues to the northward, holding up lower, but persistent crests of the northern Blue Ridge. This drop-off in elevation suggests that it marks the northern termination of the Ancestral Blue Ridge. The lower crest levels north of Manassas Gap have suggested a former peneplain to many workers in this vicinity and are so regarded by Fenneman (1938). They could thus represent an old Potomac strath through the Blue Ridge which has been uplifted by faulting and dissected by post-fault erosion.

Location of Fault Trace in Virginia

The trace of the Blue Ridge Border fault in North Carolina can be seen clearly on Plate 1. Farther north, in Virginia, it is obscure but none the less straight and persistent. It is not feasible to reproduce all the topographic maps to show it throughout this great distance, but the fault trace can be located on the 30-minute topographic sheets of the United States Geological Survey from the description of its apparent position given here. The scarp is a feature of such major proportions and has been so greatly reduced by erosion that it cannot be seen to advantage on the individual maps. To be seen adequately the maps should be assembled so that the fault line can be seen over considerable distances.

Passing immediately west of Mount Airy in North Carolina the fault trace appears to go a few miles west of Stuart on the Stuart, Virginia, sheet. On the Christiansburg sheet it can be seen 1 mile east of Dillons Mill Post Office. On the Bedford sheet it passes through Boones Mill, along the eastern foot of Linville Mountain, through the town of Hardys Ford, through Chamblissburg, about 1½ miles east of Pilot and Flat Top mountains, and about 1 mile west of Bedford. On the Lynchburg sheet the fault trace passes east of Cifax, through Perrowville and Coffee, and across the James River at Bethel. On the Buena Vista sheet it is indeterminate between the James River and Lowesville. It is probably on either the northwest or southeast flank of Tobacco Row Mountain, but there are multiple possibilities here, and it cannot be located by topography alone. It seems to pass about 2 miles west of Lowesville and then through Massies Mill. On the Buckingham sheet it apparently follows the headwater reach of Cub Creek, passing through the gap at its head between Horeshoe Mountain and Three Ridges. Farther northeast it passes close to Slaughters, Lodebar, and Batesville. On the

Harrisonburg sheet it passes through Hillsboro, about 1½ miles east of Whitehall and along the eastern foot of Buck Mountain. On the Gordonsville sheet it seems to pass about 1 mile east of Stanardsville and along the eastern foot of Banks and Gaar mountains. On the Luray sheet it goes through Slate Mills and Boston and about 1 mile east of Viewtown. On the Thoroughfare Gap sheet it passes along the northwestern flank of Watery Mountain near its northern end, about 1 mile west of Plains, and through Halfway. In this region the trace, as located by topography, is nearly coextensive for some 20 miles with a fault shown on the geologic map of Virginia (Stose, 1928) as a high-angle structure which cuts the Triassic Catoctin Mountain border fault. On the Harpers Ferry sheet the fault appears to pass close to Oatlands and Leesburg and to be associated with the orientation of the Potomac River between Conrad Ferry and its confluence with the Monocacy River of Maryland. North of this point the fault is a recognized structure shown as a Triassic feature on the geologic maps of Frederick County, Maryland (Jonas and Stose, 1938), and of the State of Maryland (Mathews, 1933).

The trace is not only a smooth, slightly curved line throughout but is essentially an extension of the same line which was described under the discussion of the fault trace in North Carolina (Pl. 1). This slight curvature brings the strike into more northerly orientations in the northern parts of the line (Pl. 3). The only discrepancy is the presence of the several offsets shown on Plate 3 and discussed above in the section on Offsets.

It would thus seem plausible that the east front of this northern part of the Blue Ridge, where it is an actual ridge, is an extension of the same structure which exists farther south where it is a more obvious fault scarp. Since the Piedmont is lower and well peneplaned, one concludes that the valleys of the Paleozoic area to the west represent the dissection of a plateau of which the east side of the Blue Ridge was originally the bounding scarp.

Blue Ridge Border Fault North of Virginia

Evidence for normal faulting in the Maryland-Pennsylvania-New Jersey region has been presented in some detail by Stose (1927) who notes a discordance of levels between the remnants of the Kittatiny peneplain to the west and those of the Schooley to the east. He ascribes this discrepancy to post-Cretaceous normal faulting. A strong zone of high-angle faulting is shown on the Pennsylvania geologic map (Stose and Ljungstedt, 1930) along the northwestern edge of the Reading Prong. West of his assumed fault Stose finds the summit levels accordant in two planes. The higher he refers to the Kittatiny peneplain, the lower to the Weverton, following Keith (1892–1893). East of the fault he finds two corresponding levels correlative with those on the west. These (the Schooley and the Honeybrook) he believes to be the same two surfaces on the downthrown block; the amount of throw in the fault being about 500 feet. He shows no displacement of the Harrisburg or younger surfaces.

These findings of Stose suggest that the writer's conclusions concerning the fault origin of the Blue Ridge scarp in its southwestern reaches are also applicable to its northern extension in Maryland and Pennsylvania. The vertical displacement of the fault is probably less here than it is farther south where the maximum relief of the Blue Ridge scarp is found, but a fault of this length and character could have variant displacement throughout its length. The ancestral Southern Appalachians, which seem to have stood up as a mountainous zone on the Schooley surface, probably had their northern end in the general latitude of Front Royal, Virginia, and extended southwestward lending greater elevation to the upthrown block, not only in the Blue Ridge, but also in the more resistant ridges of the Ridge and Valley province northwest of it.

The Harrisburg surface was made by etching out the softer material on both sides of the Blue Ridge in Northern Virginia, Maryland, and Pennsylvania, to levels below those of the Schooley and Weverton surfaces. Thus an elongated tongue of this lower or Harrisburg surface (and possibly younger surfaces as well) persists southward along the eastern foot of the Blue Ridge in the softer rocks of the Triassic, adding considerably to the stature of the Blue Ridge front in terms of local relief above its immediate environs.

The maximum development of the Harris-

burg surface is, in central Pennsylvania, a region where over long distances the crystalline basement rocks are absent from the upthrown fault block. This conspicuous absence, a plausible cause for the localization of the Susquehanna Valley in pre-fault time, would have been doubly responsible for the rapid reduction of the fault scarp and the cutting of the Harrisburg peneplain; for not only did it present weak rocks for reduction, but also assured the presence of an arterial stream system to reduce them. The absence of the Blue Ridge scarp across the valley of the Susquehanna is thus explained, and the work of Stose (1940) in the Poconos and the Reading Prong suggests that the Blue Ridge border fault is expressed topographically farther north although in reduced degree.

The amount of dissection requisite to produce the large areas incorporated in the Harrisburg surface may seem to be too much to account for in post-fault time. This difficulty becomes especially noticeable when one considers that the Blue Ridge scarp has been laid back only 10 to 15 miles in the same period. However, the Harrisburg peneplain appears only on the less resistant rocks. Fennemen (1938, p. 260–261) describes it as follows:

> "The Harrisburg cycle took only a small fraction of the time consumed in the Schooley cycle. This is plain from two facts: (1) It is limited to weak rocks or to the vicinity of streams. (2) Its level rises upstream so much that only on large streams or lower courses can it be treated as a general peneplain whose base level was the sea. Elsewhere, the base level was local, and it was different in each drainage basin."

A great part of the Harrisburg surface was developed on Paleozoic limestones. Such rocks are rapidly reduced by solution in humid climates such as those which prevail in southeastern United States.

Most of the present remnants of the Harrisburg surface are preserved on Paleozoic and Triassic shales. These also are patently less resistant than any of the crystalline silicate rocks.

There is a notable dearth of literature on the geomorphic relationships of the Piedmont surface of the Southeast, but the writer believes it to be Schooley in age and correlative with the Schooley peneplain on the downthrown block of Stose's fault. Likewise, certain strath levels of the Blue Ridge Upland of the Southeast, as well as many of the higher-level summits of the Blue Ridge in northern Virginia and Pennsylvania, are thought to be correlative with the Schooley (Kittatiny) surface on the upthrown block of the fault postulated by Stose.

Since the Blue Ridge Border fault diminishes in throw toward the north, that part of the elevation of the Schooley surface, which is the result of upfaulting, is a progressively diminishing component of its total elevation. Thus in the south a fair share of the elevation of the upfaulted Schooley is the result of upfaulting, but in New Jersey, where the difference in elevation between adjacent remnants of the Schooley and Kittatiny surfaces is a diminishing amount, the greater share of the height of the Kittatiny (upfaulted Schooley) as well as that of the Schooley on the downthrown block is the result of the general uplift of the region on both sides of the fault—an uplift which may have taken place in the earlier stages of the same deformation which later produced the fault.

More briefly, in any one place, the throw of the Blue Ridge Border fault equals the elevation of the Kittatiny surface minus the elevation of the Schooley surface and the general uplift aside from faulting equals the elevation of the Schooley minus the elevation of the Harrisburg.

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TERRACED HIGHWAY SIDE SLOPES IN LOESS, SOUTHWESTERN IOWA

BY CHARLES S. GWYNNE

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ABSTRACT

In 1940 the Iowa State Highway Commission made use of an experimental terraced type of design for highway side slopes along a 4-mile east-west route through the loess of Harrison County, Iowa. Relief along the route is 250 feet, and road cuts as deep as 80 feet were required. Terraces were 15 feet high and 15 feet wide; treads were sloped along the length and toward the base of the risers. It was believed that this design would have advantages over the conventional side slopes of 1-to-1 to 3-to-1 ratio. The risers, being in loess, would tend to maintain verticality, but the hazard involved in single vertical cuts of as much as 80 feet would be avoided. Such slopes would be less subject to raindrop and rivulet erosion.

Spalling of risers, principally the result of changing stress conditions, commenced within a year. Almost all risers have now been affected to some extent. The greatest changes have been the result of rivulet erosion down the risers, presently developing as a consequence of the accumulation of sloping piles of material on the treads. Deterioration has been greatest on the slopes of the south side of the road; the loess does not dry out as readily, and freezing becomes more effective; more debris accumulates on the treads, and slope wash increases.

Although the slopes now have a ragged appearance, the design is considered reasonably successful as far as maintenance requirements are concerned. Further experimentation is being considered.

INTRODUCTION

In 1940 the Iowa State Highway Commission carried out a program of improvement and relocation on State Route 127 west of Magnolia, Harrison County, southwestern Iowa, and in so doing adopted an unusual type of design for the road cuts. This design (Engineering News-Record-Anonymous, 1940), in brief, is one of terracing the sides of the cuts through the loess. Since construction, the terraces have been considerably modified by erosion. The design, the principles used in adopting it, and the post-constructional changes resulting from instability of the material and from erosion upon the side slopes will be described and interpreted.

DESCRIPTION OF AREA

The 4-mile section of State Route 127 thus improved extends westward from Magnolia, on the divide between Allen Creek and Willow River, to the junction with U. S. Route 75 at the margin of the Missouri River flood plain (Fig. 1).[1] The 2 western miles were relocated. Relief along the section, through a distance of about 4 miles, is 270 feet. The topography is typical of that of the loess-covered country adjacent to the Missouri River flood plain. It has a relief as great as approximately 250 feet in a square mile and is practically all in slopes, up to as much as 25 per cent, except for narrow strips of bottom land adjacent to the larger streams.

[1] Across secs. 31 and 32, T. 80 N., R. 44 W. (Magnolia Township), and secs. 34, 35, and 36, T. 80 N., R. 45 W. (Raglan Township).

The area is thus well drained (Fig. 2; Pl. 1). There are 19 natural drainage lines in the 2 miles of the relocated section and 11 in the unrelocated section.[2] The familiar "cat-step" terraces characteristic of the steep hillsides on loess

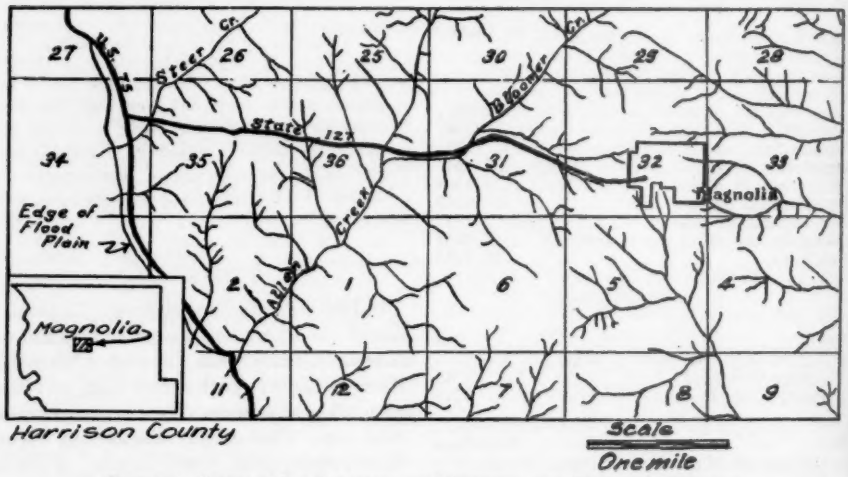

FIGURE 1. SKETCH MAP, PORTIONS OF MAGNOLIA AND RAGLAN TOWNSHIPS

in western Iowa are present on some of the slopes (Shimek, 1910, p. 283–284).

The area is covered with Peorian loess, with an estimated thickness of as much as 100 feet at the margin of the Missouri River bottoms. The loess thins rapidly eastward along the route, but all road cuts except one are in Peorian loess. Loveland loess and underlying glacial drift were exposed beneath the Peorian in a road cut in the west half of section 31 at the time of construction.

CHARACTERISTICS OF LOESS

In the absence of petrographic studies of the loess of Harrison County, the description of the loess of Nebraska, Kansas, and South Dakota (Mielenz, Holland, and King, 1949) is cited as reasonably applicable to the loess of western Iowa, although the latter has a different source area.

Loess is typically grayish brown, massive, porous and friable. Small tubes trend in all directions, but predominantly vertically; many still contain fragments of roots which formed them. Loess is composed of angular to subangular, quartzose and feldspathic silt and fine sand, each grain being surrounded by a grain of montmorillonite, which binds them together at points of contact. Calcite is distributed throughout the loess largely as silt-sized granules, rather than as a cement.

When undisturbed loess is impregnated with a thermoplastic resin, thin sections reveal the structure to be open, with little interlocking of the grains. Voids occur in intergranular spaces, irregular spaces due to local consolidation on a microscopic scale, tubes related to roots, and cracks.

Mechanical analyses and tests made in the laboratory of the Iowa State Highway Commission, Ames, Iowa (F. H. Dorheim, personal communication) (Table 1) cover the grain-size and behavior characteristics of loess from the route and from other places in the area of thick loess. Two are from Route 127; three from localities in Monona County, approximately 25 miles north-northeast of Magnolia and 8 miles east of the margin of Missouri River flood plain. Most of the particles are of silt size, and the content of clay ranges from 23 to 32 per cent. Atterburg limits are in keeping with the particle-size distribution.

[2] Allen Creek at the eastern margin of the relocation, the largest stream in the area, has its headwaters about 12 miles northeast. At the highway crossing its valley is about 350 feet wide at the bottom. Smaller valley crossings are those of Little Bloomer and Steer creeks, each approximately 60 feet below its surroundings, with widths at the bottom of approximately 200 feet. Little Bloomer is in the unrelocated section. Many small tributaries of the three streams cross the route.

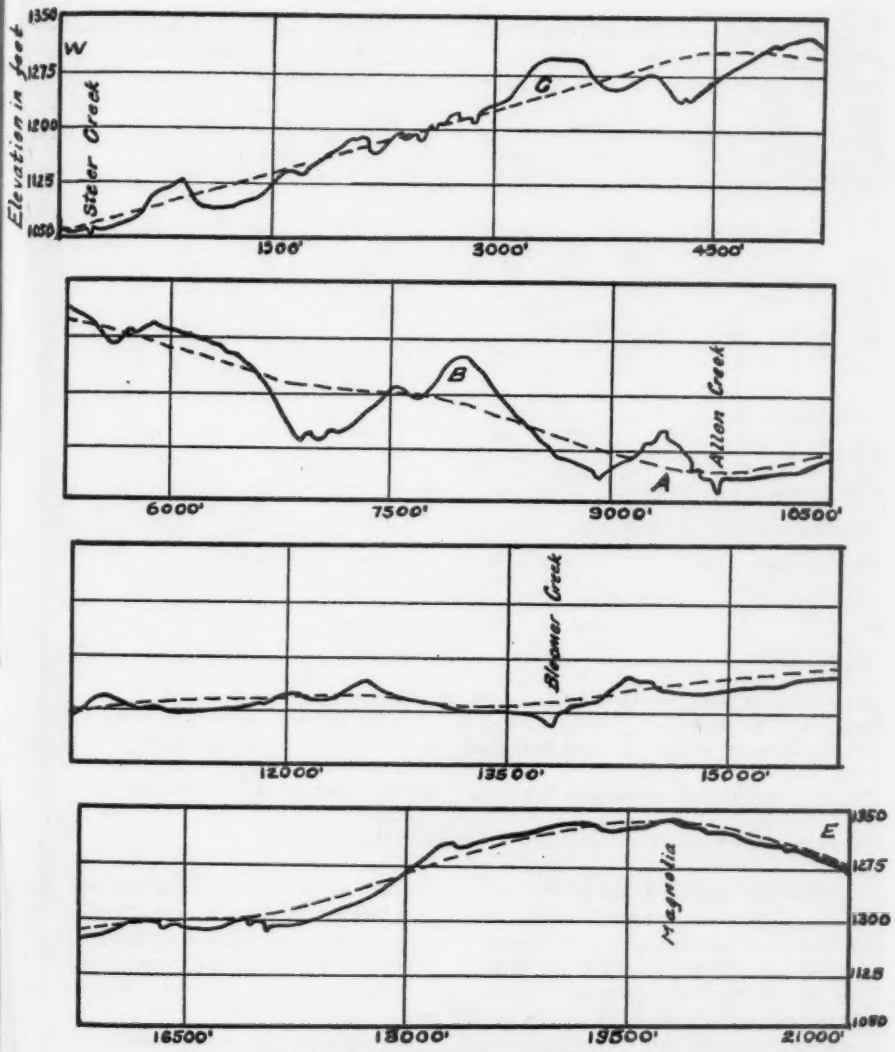

FIGURE 2. PROFILE, STATE ROUTE 127

From Magnolia to junction with U. S. 75. Data from plan and profile, Iowa State Highway Commission. Ground profile: solid line. Road profile: dashed line. A, B, C locate points referred to in Figures of Plate 2.

DESCRIPTION OF DESIGN

The relocation was made with the object of straightening the road, and this necessitated crossing steep-sided ridges. To avoid grades which were too steep required deep cuts in the ridges and thick fills in the valleys. Some of the cuts were to have a depth of about 80 feet. Conventionally, the back slopes of such deep cuts are made on a 1-to-1 or 3-to-1[1] ratio, depending on the type of material. It was known

[1] Three feet horizontally for each vertical foot. This usage, that of the Highway Commission, will be employed in later references.

that rainwash and rivulet erosion on such slopes would be severe. The loessal property of maintaining relatively vertical faces was well known to the designers, and road cuts, mostly shallow, on other highways in western Iowa have been made with vertical faces. Vertical cuts up to approximately 50 feet in height, for example, were used in the construction of U. S. Route 275 through the loess hills of Fremont and Mills counties (the second and third counties south of Harrison), a distance of 50 miles.[4] Construction was completed in 1935. Side slopes are considered to be in a satisfactory condition, though the original vertical faces have been destroyed in many places, and the slopes now have a ragged appearance. Maintenance costs have not been considered out of line. Vertical cuts were also used on U. S. Route 30 north of Council Bluffs, with similar results. The county engineers of Harrison County use vertical cuts on the secondary roads, with a slope of 1¼-to-1 to a height of 5 feet at the base. The basal slope allows for the accumulation of falling material. Various slopes up to 4-to-1 were experimented with before adopting this type of design in Harrison County.

TABLE 1.—MECHANICAL ANALYSES, LOESS SAMPLES, HARRISON AND MONONA COUNTIES, IOWA STATE HIGHWAY COMMISSION LABORATORY, AMES, IOWA

		Sample No.				
		1	2	3	4	5
Per cent	Fine Sand	2	2	2	3	14
	Silt	71	73	66	70	63
	Clay	27	23	32	27	23
Liquid limit		38	36	46	39	30
Plastic limit		24	25	26	24	21
Plastic index		14	11	20	15	9
Shrinkage limit		20.4	24.3	20.3	20.9	18.8
Shrinkage ratio		1.72	1.64	1.74	1.72	1.75
Class name		Silty Clay Loam	Silty Clay Loam	Silty Clay Loam	Silty Clay Loam	Silty Clay Loam
P.R.A. Class		A-4	A-4	A-7	A-4	A-4

No. 1—Near SE corner sec. 33, T. 8 N., R. 43 W., Harrison County.
No. 2—N of W¼ corner, sec. 31, T. 80 N., R. 43 W., Harrison County.
No. 3—Composite sample from eight holes along State Route 183, between Soldier and Ute, Monona County.
No. 4—Composite sample from eight holes along State Route 183, between Soldier and Ute, Monona County.
No. 5—Station 354 + 00, 13 feet right, on State Route 37, Monona County.

It was believed that this loessal property of maintaining vertical faces could be used in this program of improvement on State Route 127. However, a single vertical cut to the full depth of 80 feet was obviously impractical. The limiting height at which a soil material will stand vertically is a function of the shearing resistance, particularly the cohesive component (Taylor, 1948, p. 453–455). While data are not available, there is no doubt that in a cut of 80 feet the material would be overstressed and

[4] Description which follows is based upon discussion with engineers of the Iowa State Highway Commission.

PORTIONS OF MAGNOLIA AND RAGLAN TOWNSHIPS
Production Marketing Administration photograph

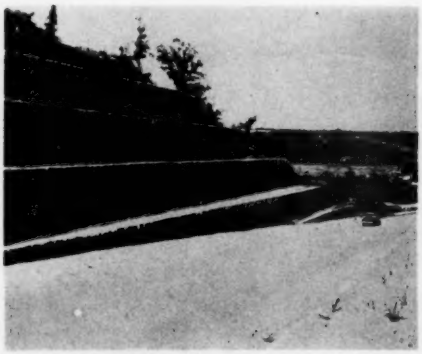

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

TERRACES, STATE ROUTE 127

slides would result. A single cut of 80 feet was undesirable also because of the hazard involved in spalling. The hazard would exist during construction. Later, the loess might break off into blocks or slabs which would slough off or topple into the ditch or the roadway, dangerous to traffic as well as unsatisfactory to maintenance.

It was decided to adopt a terraced design and to carry it out on all road cuts through the entire 4 miles. In this design, the sides of the center and side-hill cuts through the hills, some of them as much as 80 feet deep, were made in the form of steps or terraces. Except for the top and bottom steps, the height was 15 feet; the minimum width was also 15 feet. They were made with a slope of half an inch per foot downward toward the bottom of the next riser, and also were given a gentle slope along the length, in the direction deemed most suitable for carrying surface drainage. The natural vegetated slope above the top terrace was left unmodified. Even where this slope was toward the cut it was at a low angle; drainage over the top of the cut would be distributed and minor.

It was believed that, with these details of design, there would be no runoff over the edges of the terraces. Rain falling on the terraces would either soak in or any collected would tend to drain slowly along the length at the base of the riser. In a few places where short natural high-gradient drainage lines intersected a cut, a corrugated-iron drainage pipe, 24 inches in diameter, was installed to carry the runoff. This was placed beneath each terrace and carried out over the risers, and finally beneath the road to a natural waterway.

While more or less experimental, it was hoped that this terrace type of construction would provide back-slopes which, on the risers, would remain nearly vertical for a long while, and which would obviate or decrease the need for ditch cleaning.

Post-Construction Changes

These road cuts were first observed by the writer in the summer of 1941. By that time, the risers of some of them had already started to break down, but most were relatively unaffected (Pl. 2, figs. 1, 2). Mr. C. B. Anderson, Road Design Engineer (Personal communication) reports that after some exceptionally heavy rainfall which occurred not long after construction was completed, lengthwise erosion at the base of some of the risers had been sufficient to precipitate some slumping; also, that in places the upper few feet of the risers were coated with a plaster of material which had streamed over the edge of the tread as a rather plastic mass, suggesting that the surface of the tread above had been flooded. Since these earlier observations, all of the road cuts have been more or less affected by further post-construction changes. Much of this has taken the form of spalling of slabs of loess from the risers. This can be noted in all stages at the present time (July 1950). There has also been a considerable amount of minor crumbling. However, the faces of the cuts are now marred not only as a result of the spalling and crumbling, but also by subsequent rivulet erosion.

The deterioration of the terraces is much greater on the south than on the north side of the road. The edges of the treads on the south side are estimated to have retreated on the average a foot or more, and the debris which mantles most of them forms a continuous slope from the face of the riser to the edge of the tread for most of their distance, except near the ends.

PLATE 2. TERRACES, STATE ROUTE 127

FIGURE 1. NORTH SIDE OF ROAD, AT B, FIG. 2 (1941)
A typical side-slope in its original condition. Terraces at A of Fig. 2 show in the distance.

FIGURE 2. NORTH SIDE OF ROAD, AT B, FIG. 2 (1941)
West of Fig. 1. Spalling prominent; rivulet erosion beginning on two lower risers.

FIGURE 3. VIEW EASTWARD, AT B, FIG. 2 (MARCH 1948)
Slumped material on treads on south side, at right, extends to edge. Deterioration of north side, at left, not considered excessive.

FIGURE 4. SOUTH SIDE OF ROAD AT C, FIG. 2 (MARCH 1948)
Dark and light areas, respectively, show distribution of moist and dry loess. Moist loess, top riser, extends farther from surface below larger trees.

FIGURE 5. NORTH SIDE, EAST END OF CUT AT B, FIG. 2 (1948)
Original faces of risers unmodified in many places. Debris rarely extends to edge of terrace. Rivulet erosion not prominent.

The effects of rivulet erosion, of runoff down the surface of the entire cut, is much more prominent.

Walking the length of these terraces on the south side is generally difficult because of the sloping debris (Pl. 2, fig. 3) on the treads. At the time of a detailed examination in March 1948, the slopes on the south side were saturated and even frozen, except for parts of the risers which had thawed and dried out (Pl. 2, fig. 4). There was no way of knowing whether there had been lengthwise drainage on most of the treads, since they were so generally mantled with debris. There may have been, at times, if much of the tread was saturated and frozen. However, those few treads on the south side which had little or no debris on them had no visible evidence of lengthwise drainage.

In the cuts on the north side of the road, the original edges of the treads are still preserved in many places, and the debris rarely extends to the edge (Pl. 2, fig. 5). Walking the length of these terraces is easy, since the outer part of the tread is still uncovered for an estimated average width of approximately 5 feet. At the time of the detailed examination in March 1948, the slopes on the north side were dried out and unfrozen. There was no visible evidence of there having been drainage along the length of the terraces, in the places where little or no debris had accumulated on the treads. Treads on the north side had faint mudcracks, about 5 inches across, in several places where they were not covered with debris, showing that at some times the surface material became saturated. Though the ingress of water may have ceased at such times, there was no evidence that the water ever accumulated and moved over the surface in amount sufficient to cause erosion along the length or over the edges of the treads.

A rather scant vegetation has spread over the terraces and the debris upon them. Trees, mostly cottonwood, up to 15 feet or more in height, are fairly numerous. It is believed that there are more of them on the south than on the north side of the road.

The westernmost of the deep cuts, at the top of the ascent from the Missouri River bottoms, has been most affected by spalling and erosion, and on both north and south sides.

Columnar jointing, generally accepted as a characteristic of loess, has not developed on these terraces, except possibly in places on the top risers. However, rivulet erosion has produced the appearance of columnar structure in many places.

Discussion of Spalling and Erosion

The splitting or spalling off of slabs and sheets of loess was evident as early as 1941, within about a year after construction was completed, and it is still continuing. Among others besides the writer, it has been noted by M. G. Spangler, Department of Civil Engineering, Iowa State College (Personal communication).

Reasonably, this type of construction results in the lessening of pressure upon the uncovered loess, and the disturbed strain conditions thus set up might account at least for the initiation of the spalling. Spalling is believed somewhat less at the ends of the terraces and on the top risers, where changes in strain brought about by excavation are less. Later wetting and drying, or freezing and thawing, may aid in the spalling.

Slabs observed in the process of separation were up to approximately a foot wide and a rod or so long along the face. Some of these slabs, though separated from the main mass of the loess, do not fall for some time. Many of them become weakened at the bottom, and then settle back against the riser. There is also considerable spalling off or crumbling of smaller amounts of loess from the faces of the risers. This too accumulates at the base of the riser. Less frequently, the larger slabs fall forward, and debris may extend to the edge of the tread; the fall may occur with such force that some of the edge may be broken away. Material which falls in this manner is more scattered, and does not form a surface sloping away from the riser. In any case, this slow accumulation of debris, usually highest at the base of the riser, results in a slope down which there may be runoff, particularly if the surface of the debris is saturated or frozen.

The exposure conditions on the two sides are

quite different. The north side gets the sun all year long; the south side is in the shade, wet or frozen for several months. There was probably no runoff from most of the piles of debris on the terraces on the north side, as they are hummocky and generally remain unfrozen; the debris is sufficiently porous so that the water soaks in. Any runoff which does occur usually soaks into the tread surface, of which there would still be a considerable unmarred width. However, runoff over the edges, and consequent rivulet erosion of the risers, does occur where large piles of debris extend to the edge of the tread.

Runoff has been much greater from the accumulated debris on the terraces of the south side, where the debris is saturated or frozen, and where much of it on most levels extends to, or nearly to, the edge of the tread. This is believed to explain the greater deterioration on the south side of the road cuts.

Spalling of loess from risers, as described above, is certain. To the writer it would appear to be related (1) to wetting and drying, and freezing and thawing; (2) in a general way to changed stress conditions within the mass, incident to the excavation; (3) to a combination of the two.

The dried-out part of the face of the riser would be narrower toward the bottom. Being more cohesive than the moist, the dry loess would shear away from the rest because of the softening of the clay mineral in the latter.

The result of changing stress conditions within the loess mass can be evaluated and related to the spalling only uncertainly. In unindurated materials cut to a vertical face, shear would develop at an approximate angle of 40° with the horizontal. Slide would result if the vertical face were high enough, and the mass behind it great enough to overcome the cohesiveness of the material. These terraces are not high enough to result in such failure.

However, the material prior to excavation had been under stress from the overlying load for thousands of years. In that time might not shear at a steep angle with the horizontal have developed? Excavation gives the material a chance to move along the incipient planes of sliding.

Such spalling of the loess faces may throw further light upon the origin of the "cat-steps" of the loess hillsides. Sheet erosion or creep down the slopes would disturb the stress conditions within the mass. If this resulted in the breaking away of sheets as it has on the risers of the road cuts with a tendency for the spall to move out at the bottom, the development of "cat-steps" would follow.

Vegetation is not believed to affect greatly the breakdown of the terraces. Trees of good size, with deep root penetration, open up the loess so that more water enters and there is less to run off. This is shown in several places on the south side. The zone of moist loess near the surface extends to greater depth beneath trees. Trees growing near the edge, on the other hand, may tend to split off material from the riser.

As has been noted, both sides of the most western of the deep cuts have been more affected by spalling and erosion than the sides of the cuts farther east. Location and loess composition may help to explain this. The cut is at the top of the long grade up from the Missouri River and receives more of the force of wind and rain from the west. Also, the material here, being nearer the source, presumably has a higher proportion of larger particles, and less clay.

Conclusions

This terrace design is believed to be an improvement over the conventional side slopes, as far as the general effects of erosion are concerned. At the present rate, the terraces will be destroyed sooner on the south than on the north sides of east-west roads, and the faces will assume the steepness of natural hillsides in loess, or close to a 1-to-1 slope. The destruction will start with spalling, mostly related to the release of stress on the loess beneath the original surface. Runoff down the piles of debris thus created will follow. Runoff down the face of the entire road cut will eventually develop. In the course of this there will be much wearing away of the face and deposition at the bottom of the cut with probable required maintenance in the clearing of ditches. The runoff will be almost entirely that which falls on the face, so it will not be great. So far the maintenance problem has not been a serious one (Personal communi-

cation, John A. Butter, Administration Engineer, Iowa State Highway Commission). The gradual spread of a vegetative cover will tend to stabilize the slope.

The Iowa State Highway Commission does not have in immediate prospect any construction involving deep cuts through loess. The type of side slopes which would be used, when or if the occasion for deep cuts arises, is uncertain. The commission, in shallow cuts through loess, is inclining more toward 2-to-1 or 3-to-1 slopes. These are covered with straw and seeded as soon as possible, and every effort made to stabilize the surface through the growth of vegetation. The Iowa Highway Research Board is considering an investigation of loess and glacial material of Iowa, and it is possible that this may include study of side slopes of different types.

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SUBDIVISION AND DATING OF THE CAMBRIAN OF EASTERN PENNSYLVANIA

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ABSTRACT

Although Cambrian rocks from eastern Pennsylvania have been known for over a century, their interpretation has never been satisfactory. A basal quartzite is overlain by a thick sequence of dolomitic limestone. The quartzite is Early Cambrian. In the limestones occur rare invertebrate faunules and many calcareous algae by means of which it is possible to identify the upper third as Trempealeauian, the middle third as Dresbachian, but the age of the lower third is still uncertain. Lithologic changes coincide with paleontological differentiation. For the three parts of the limestone we here use, in descending order, the local formational names Allentown (restricted), Limeport, and Leithsville.

THE PROBLEM

Cambrian age of sedimentary rocks in eastern Pennsylvania has long been recognized. Four areas, the Lehigh Valley in Lehigh and Northampton counties, and Durham Valley, Buckingham Valley, and the vicinity of Langhorne, in Bucks County, are known, plus a few scattered, small occurrences (Fig. 1). Attempts to name and correlate the Cambrian formations accurately in these areas have met with partial success. Because of recent work in Bucks County and the Lehigh Valley, a better interpretation may now be offered.

IN RETROSPECT

Cambrian rocks in Pennsylvania occupy two principal regions: a long, narrow belt constituting part of the limestone valley extending from the Delaware River to the south-central border of the State, and an irregularly shaped area in central Pennsylvania. A few smaller patches lie to the southeast of the first. Years ago, H. D. Rogers (1836) recognized in the Great Valley thick, blue limestone with chert, iron and veins of calcite. Two years later (1838) he suggested a thickness of 6000 feet. In his remarkable "Geology of Pennsylvania" (1858), Rogers described the "Primal" sandstone at the base of the sedimentary rocks of the State and correlated it with the Potsdam of New York. Above this he identified the "Auroral

Magnesian lime stone". Between the Delaware and the Schuylkill he hinted vaguely of two parts to the limestone and indicated that it is in part Cambrian.

FIGURE 1.
SKETCH MAP SHOWING CAMBRIAN LOCALITIES IN EASTERN PENNSYLVANIA REFERRED TO IN THIS PAPER

Black areas in Bucks County are Cambrian only. Shaded areas in Lehigh County are Cambrian and Ordovician.

In the Second Pennsylvania Geological Survey's report of Lehigh and Northampton Counties (1883), J. P. Lesley gave the Lehigh Valley sequence as:

Trenton limestone
Chazy limestone
Calciferous limestone
Potsdam sandstone

Prime, in the same volume, discussed the "Magnesian limestone" (Roger's term); he included the Chazy and Calciferous. He noted that the lower part along the south side of the valley has many calcite veins, mica ("damourite") slate, and some sandstone. The higher beds to the north were said to carry oölites, much breccia and flint. He mentioned obscure traces of fossil shells and "fucoids".

In 1909, E. T. Wherry proposed a breakdown of the Lehigh Valley Cambrian under geographic names. Following the work of Stewart Weller in New Jersey (1903), Wherry used Hardyston for the Lower Cambrian quartzite to supplant the misused Potsdam. Overlying this came 1500 feet of Lower-Middle Cambrian, gray, dolomitic limestone with sandy and cherty beds and buff-colored shale to which he gave the name *Leithsville*. Above the Leithsville he assigned 2000 feet to his Allentown, Upper Cambrian dolomitic, gray to white limestone with much oölite and many "*Cryptozoa*". These two limestones were separated lithologically and by the presence or absence of the algae. B. L. Miller's report on the Allentown Quadrangle (1925), simply recognized some 3500 feet of Cambrian and Ordovician limestones. J. M. Hills (1935) adopted Wherry's nomenclature, drew the Leithsville-Allentown contact somewhat higher: 1500–1600 feet to the higher, 800 to 950 feet to the lower formation. Consequently, some algal-bearing beds were included in the Leithsville, contrary to Wherry's original definition. Hills published a columnar section but did not state if it be composite or to be seen entire at any particular place. From his data it seems as easy to draw the contact at any one of several other levels.

Miller's descriptions of the Cambrian in Northampton (1939) and Lehigh (1941) Counties are essentially identical. He adopted Wherry's term, Allentown, rather than Stose's Conococheague (Stose, 1909, 1931), but used Tomstown instead of Leithsville. He gives the sequence:

	feet
Ordovician	
Jacksonburg-limestone	700
Beekmantown limestone	1000–1200
Cambrian	
Allentown limestone	1500–1600
Tomstown limestone	900–1000
Hardyston quartzite	25–400

The U. S. Geological Survey folios for Philadelphia (Bascom, *et al.*, 1909a) and Trenton (Bascom, *et al.*, 1909b) lumped the Cambrian and Ordovician limestones of southeastern Pennsylvania under the term Shenandoah. A like name has been long in use by the New Jersey Survey, which designates its Cambrian and Ordovician limestones collectively as the Kittatinny.

TABLE 1.—EVOLUTION OF TERMINOLOGY OF "CAMBRO-ORDOVICIAN" FORMATIONS OF EASTERN PENNSYLVANIA AND NEW JERSEY

H. D. Rogers, 1858	*J. P. Lesley and F. Prime, 1883*	*U. S. Geol. Surv. Folios, 1909*
Magnesian limestone	Chazy limestone	Shenandoah limestone
Potsdam sandstone	Calciferous (Magnesian) limestone	Chickies quartzite
	Potsdam sandstone	
N. J. Geol. Survey, various dates	*E. T. Wherry, 1909*	*G. W. Stose, 1931*
Kittatinny limestone	Allentown limestone	Beekmantown, (?) limestone
Hardyston quartzite	Leithsville formation	Conococheague limestone
	Hardyston quartzite	Elbrook limestone
		Hardyston quartzite
B. L. Miller, 1934	*J. M. Hills, 1935*	*B. L. Miller, 1939, 1941*
Beekmantown limestone	Beekmantown limestone	Beekmantown limestone
Conococheague limestone	Allentown limestone	Allentown limestone
Tomstown limestone	Leithsville formation	Tomstown limestone (Leithsville limestone)
Hardyston quartzite	Hardyston quartzite	Hardyston quartzite

N. B. No correlation is implied in this table.

Stose (Bascom, *et al.*, 1931) broke down the Shenandoah in east-central Bucks County as follows:

Ordovician	feet
Beekmantown limestone (?)	1000
Cambrian	
Conococheague limestone	900±
Elbrook limestone	500±
Hardyston quartzite	300±

In "Limestones of Pennsylvania", B. L. Miller (1934) used Stose's Buckingham Valley sequence. He mentioned only briefly Durham Valley, gave no stratigraphic data. For the Lehigh Valley he used Conococheague rather than Allentown, Tomstown instead of Leithsbille. Table 1 summarizes the terminology.

The inclusive terms, Kittatinny and Shenandoah, are useless and untenable in eastern Pennsylvania. The Conococheague, Elbrook, and Tomstown imply an unwarranted correlative assumption with type areas of these three in south-central Pennsylvania as finally defined by Stose (1909).

The sequence there is (1909):

Ordovician	feet
Beekmantown limestone	2300
Cambrian	
Conococheague limestone	1635
Elbrook formation	3000
Waynesboro formation	1000±
Tomstown limestone	1000±
Antietam sandstone	500–800
Harpers schist	2750
Weverton sandstone	1250

This succession and the stratigraphic limits given are in part vaguely similar to those in the Lehigh Valley, but neither the lithologic nor paleontologic data substatiate so long-range a correlation. Furthermore, no published account indicates a complete, systematic tracing through of beds from the Lehigh Valley to south-central Pennsylvania, although to be sure the limestone belt is continuous. The Durham and Buckingham areas are isolated. Willard (1949) therefore proposed to divide the Cambrian rocks of these areas as follows:

Upper Cambrian
  Allentown limestone
Cambrian (epoch unknown)
  Leithsville limestone
Lower Cambrian
  Hardyston quartzite (Lehigh Valley)
  Chickies quartzite (Buckingham Valley)

More recent studies have, however, indicated that this plan should be modified, and it is now proposed to adopt the following local terminology already in the literature for the rocks of the Buckingham and Durham areas, with one addition, the Limeport limestone, which is defined on a later page.

Ordovician
  Beekmantown
Cambrian
  Allentown
  Limeport
  Leithsville
  Hardyston or Chickies

Calcareous Algae (Stromatolites) in the Upper Cambrian of Eastern Pennsylvania

Stromatolites, long known as "cryptozoa" or "calcareous algae", are an ubiquitous feature of the Upper Cambrian limestones of eastern Pennsylvania (Fig. 2). These fossils are often so abundant that they form biostromes, or beds of uniform thickness over wide areas, which recur rhythmically throughout most, if not all, of the Upper Cambrian sequence. Thus, in our portion of the State, stromatolites were important rock-builders.

Cryptozoön fieldii and *Archaeozoön undulatum* of our Limeport formation were the dominant builders in Dresbachian (early Late Cambrian) time, while *Dolatophycus expansus* was locally abundant. During the Allentown (Trempealeauian, late Late Cambrian) cycle, the principal rock-building role was assumed by two new species of *Cryptozoön* and, to a lesser degree, by *Anomalophycus compactus*. A few reefs of the Limeport *Cryptozoön fieldii* persisted as stragglers into the Allentown.

Since the term *stromatolite* will be used often in the present discussion, we must define the term.

A stromatolite is a mineral copy or cast of the external form of an algal colony. It is essentially a laminated structure formed of thin films of calcium carbonate which were successively precipitated upon the surface of the growing colony. Thus, each film, or lamina, represents one of a series of successive shapes, or one growth stage of a series of growth stages, through which the colony passed. Interpreted in this way, a stromatolite is a record, preserved in rock, of the growth and development of the living plant colony that produced it.

These fossils were first noted in eastern Pennsylvania by Prime (1878), who did not, however, perceive their true nature. Walcott (1894) reported "a species of *Cryptozoön*" in the limestones near Easton. Later, Wherry (1909) recognized that cryptozoöns were characteristic of his Allentown formation. Stose (Bascom *et al.*, 1931) recorded stromatolites from Bucks County for the first time, and Miller (1934, 1939, 1941) published information on the local occurrence of "*Cryptozoön proliferum*" in the Lehigh Valley.

Hills (? 1934) noted that more than one species of stromatolites was probably present in the Lehigh Valley, and (1935) questioned the conspecificity of the Lehigh Valley forms with *Cryptozoön proliferum* Hall, to which previous authors had usually referred them. In 1937, Fenton and Fenton separated the so-called *Cryptozoön proliferum* Hall of the Lehigh Valley and Bucks County into two new species, *Anomalophycus compactus* and *Dolatophycus expansus*, and one new variety, *Cryptozoön proliferum fieldii*. (Pl. 2, fig. 2)

Local Details

Bucks County

Durham Creek.—The valley of Durham Creek of northern Bucks County occupies an eastward-plunging synclinorium of Paleozoic rocks. It extends westward to embrace the type locality of the Leithsville formation. Exposures are at best unsatisfactory because of their discontinuity. Mostly they are in isolated, abandoned quarries. The Cambrian sequence in the valley is:

	feet
Allentown limestone	400 (plus ?)
Limeport limestone	400–500
Leithsville limestone	800–900
Hardyston quartzite	50–300

No Beekmantown limestone has been observed. Since the highest beds identified are Allentown, the younger (Beekmantown) formation is believed to have been quite eroded. The Allentown, Limeport, and Leithsville are separated lithologically and on the presence or absence of well-established "algae". Ages and correlation are partly deduced.

The Limeport formation is poorly exposed in the Durham Valley. However, a large abandoned quarry at Finesville, New Jersey, 1¼ miles northeast of the Delaware River, in the

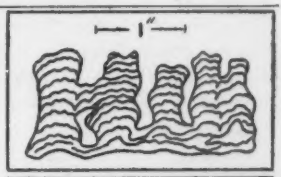
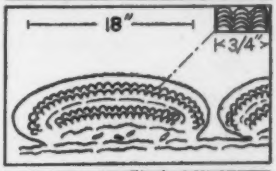
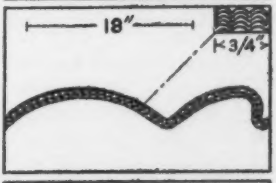
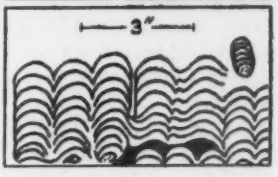
Formation	Lithology				Stromatolites			
Allentown Limestone	Oölites and conglomerates abundant	Shale rare	Sandy	Upper beds rather uniform in thickness; lower beds variable. Weathered outcrops show alternating light and dark beds, distinctly in upper part, less so in lower. Conglomerates and disconformities less abundant than in the Limeport.	Biostromes	Stromatolites	*Anomalophycus compactus*	
							Form-species A (new)	
							Form-species B (new)	
Limeport Limestone		Interbedded shales common	Very sandy	Very variable in thickness and argillaceous content. Argillaceous beds weather dirty white to cream, other beds dark gray with whitish bands or streaks. Conglomerates very abundant; many local disconformities. Shale less abundant than in the Leithsville.			*Cryptozoon fieldii*	
							Archaeozoon undulatum	
Leithsville Limestone	Oölites and conglomerates absent or scanty		Not sandy	Thick-bedded, often with masses of dark or light chert. Bedding variable toward top with thin interbedded shales. Upper beds often show whitish bands when weathered.	No biostromes	Doubtful stromatolites in upper part	?	

FIGURE 2. KEY TO THE IDENTIFICATION OF THE CAMBRIAN LIMESTONE FORMATIONS

eastern extension of Durham Valley, was opened in this rock.

Buckingham Valley.—In east-central Bucks County, Buckingham Valley is a large, isolated fault block of early Paleozoic formations surrounded by Triassic sedimentary rocks. The sequence is:

Ordovician	
Beekmantown (?) limestone, only lower beds seen, thickness unknown, identity in doubt	
Cambrian	feet
Allentown limestone	absent
Limeport limestone	400–500
Leithsville limestone	400–600
Chickies quartzite	600
Hellam conglomerate member at base.	300

Beekmantown Limestone (?): The barren Beekmantown (?) is identified only upon lithologic characteristics and stratigraphic position. Beds assigned questionably to this formation may be separated from the underlying Limeport by a reddish shale band at or near the top of the latter.

Limeport Limestone (New Formation): Between the Beekmantown (?) and the Leithsville, there are 400–500 feet of dolomitic limestones that can be distinguished by being sandier, more oölitic, and containing intraformational conglomerates and algal biostromes. On the evidence of certain algal form-species, such as *Cryptozoön fieldii* (Fenton and Fenton) and *Archaeozoön undulatum* (Bassler), plus a large, dome-shaped form not yet described, which occur at horizons close to that at which Dresbachian trilobites occur at Limeport, near New Hope, Pennsylvania, and at Carpentersville, New Jersey, these beds cannot be left in the Allentown formation where previous authors have placed them, because the restricted Allentown beds contain Trempealeauian trilobites and a different suite of algal form-species. We therefore propose to call these Dresbachian beds the Limeport formation. The Limeport formation differs from the Trempealeauian Allentown formation in being more sandy and shaly, less uniformly-bedded, and in having a greater abundance of intraformational conglomerates, disconformities, mudcracks, and ripple marks. These beds were obviously laid down in shallow waters.

The section exposed in the southernmost of two abandoned quarries at a settlement locally known as Limeport, at the eastern tip of Buckingham Valley, Bucks County, Pennsylvania, is the type locality for this formation. More specifically, the type locality is three-tenths of a mile due west of Pennsylvania State Highway No. 32, at a point 2.1 miles N.32°W. of the bridge across the Delaware River at New Hope. The beds in the north quarry are also believed to belong to this formation.

Biostromes of *Cryptozoön fieldii* and *Archaeozoön undulatum* have been found in the northern quarry, and two faunules of trilobites and brachiopods in the southern. The top beds of the southern quarry are calculated to be 180 feet below the bottom beds of the northern quarry.

We have thus taken from the bottom of the Allentown formation a thickness of 400–500 feet of beds of known Dresbachian age, and called these beds the Limeport formation.

The sections of the Limeport formation exposed at Limeport, 2 miles northwest of New Hope, Bucks County, Pennsylvania, display the following beds, the upper ones being shown in the northern quarry at that locality and the lower beds (separated from those in the northern quarry by a covered area) being visible in the southern quarry:

	feet
Platy red limestone, with some sandy beds.	20
Heavy bedded, sometimes shaly, reddish limestone, with one small reef of *Cryptozoon fieldii*	49
Covered area	about 180
Alternating beds of black limestone and light-gray limestone, containing trilobites and brachiopods	4

Plate 1.—MIDDLE UPPER CAMBRIAN DISCONFORMITY

Figure 1. Limeport-Allentown Disconformity, Nancy Run Section
Photograph by Roberts

Figure 2.—Detail of Limeport-Allentown Disconformity, Nancy Run Section
Photograph by Roberts

FIGURE 1

FIGURE 2

MIDDLE UPPER CAMBRIAN DISCONFORMITY

FIGURE 1

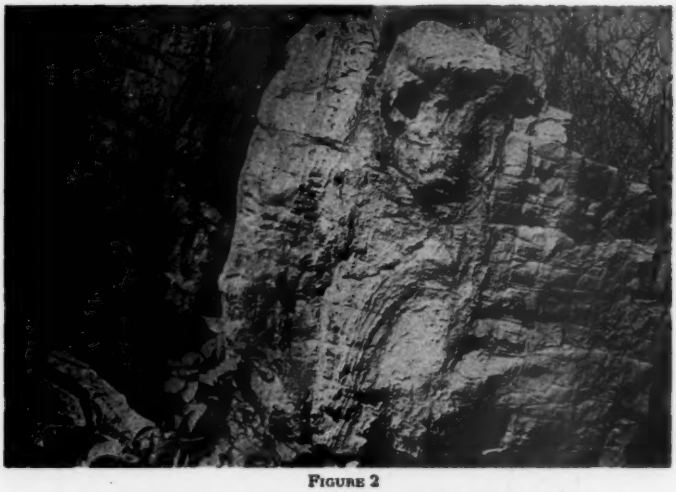


FIGURE 2

FIGURE 3

STROMATOLITES FROM THE CAMBRIAN

	feet
Light-gray basal limestone conglomerate	2
Platy black limestone containing trilobites and brachiopods	5
Light-gray limestone	1
Platy black limestone	2½
Light-gray limestone	2

At some other localities in Bucks County, beds that are correlated with these beds on the evidence of their calcareous algae [that they contain are from 400 to 500 feet thick.

LEITHSVILLE LIMESTONE: The name Leithsville limestone is preferred, rather than Elbrook, as used by Stose (Bascom, *et al.*, 1931). He so designated the beds between our Limeport and Chickies because of their supposed lithologic and stratigraphic similarity to the type Elbrook. The implied correlation is questionable. The rocks are barren, light-gray, dolomitic limestone plus shaly beds. The more massive strata tend to be finely laminated. The beds may weather whitish, locally contain black chert, mud cracks, ripple marks and quartz grains. Sericitic shale is less common than in the Lehigh Valley, but has been observed in the lower beds north of Furlong. Leithsville is proposed in conformity with the use of that name in areas to the north.

CHICKIES QUARTZITE: Chickies quartzite is used rather than Hardyston in the Buckingham area. Hardyston is reserved for those areas where the Lower Cambrian quartzite can be closely correlated with the type formation in New Jersey (Walcott, 1894; 1896; Weller, 1903, etc.). In Buckingham Valley, unlike the Hardyston to the north, the quartzite carries a basal conglomerate member believed to be the Hellam of the Hellam Hills, York County, Pennsylvania (Stose and Jonas, 1922). The Chickies in the Buckingham area is identical with that to the south in the Langhorne region, which in turn can be directly traced westward into undoubted Chickies.

Langhorne area.—The Langhorne area hardly needs comment. A band of Chickies quartzite with the Hellam conglomerate at the base crosses southern Bucks County. No limestone is present above the Chickies, due to extensive thrust faulting. As noted, this area can be correlated westward into unquestioned Chickies.

Lehigh Valley

In the Lehigh Valley, the Cambrian limestones are overlain by the Beekmantown limestone whose Ordovician age is paleontologically established, and they overlie the Lower Cambrian Hardyston quartzite, which is correlated directly with the Hardyston of northern New Jersey, where its age is paleontologically known. The Cambrian formations in the Lehigh Valley occupy between 2000 and 2700 feet, as follows:

Ordovician	
Beekmantown limestone	
Cambrian	feet
Allentown ("Conococheague")	400–500±
Limeport limestone ("Allentown" in part)	800–900±
Leithsville ("Tomstown")	800–900±
Hardyston quartzite	25–350±

ALLENTOWN LIMESTONE (restricted): The Allentown limestone, as here restricted, is dense, blue- to dark-gray, highly dolomitic limestone, bedding variable, individual strata usually 6 to 18 inches, occasionally several feet, thick. In weathered exposures, there may be noticeable alternation of dark and light banding among the beds. Shale is rare, scattered quartz grains and cross-bedded, sandy lenses abound. Oölite is usually plentiful along with ripple marks, mud cracks and edgewise conglomerate. Locally, black chert may be developed. The thickness of the Allentown is believed to be between 400 and 500 feet, but these figures are approximate.

PLATE 2.—STROMATOLITES FROM THE CAMBRIAN OF EASTERN PENNSYLVANIA

FIGURE 1.—LARGE, UNDESCRIBED STROMATOLITE, ALLENTOWN LIMESTONE, NANCY RUN SECTION
Photograph by H. G. Richards

FIGURE 2.—CRYPTOZOÖN FIELDII FENTON AND FENTON, LIMEPORT LIMESTONE, CARPENTERSVILLE, NEW JERSEY
Photograph by H. G. Richards

FIGURE 3.—UNDESCRIBED STROMATOLITES, ALLENTOWN LIMESTONE, NANCY RUN SECTION
Photograph by Roberts

In the Lehigh Valley Railroad cut east of the Front Street bridge in the City of Allentown, Pennsylvania, the upper part of the redefined Allentown formation is typically developed. The bedding is regular and the abrupt alternation of dark and light beds conspicuous. Near by, along the Central Railroad of Pennsylvania (formerly New Jersey) west of Front Street, beds characteristic of the lower part of the Allentown crop out. These are less regular in thickness than the higher beds, and the light-colored bands, instead of representing the full thickness of the bed as they commonly do in the higher beds, are confined to narrow streaks within, or at the top or bottom of, the otherwise dark-gray beds.

It appears that the even-bedded phase of Allentown (restricted) lithology is more or less confined to the higher strata, and that these higher beds are more common in the northern part of the Lehigh Valley, while only the lower, or variably bedded, portion of the restricted Allentown is represented in the Durham Valley, to the south.

The late Cambrian age of the redefined Allentown in the Lehigh Valley is based in part upon its stromatolites and correlation with other, near-by areas. The inarticulate brachiopod, *Lingulepsis acuminata*, has been reported. A Trempealeauian trilobite fauna has been found in it at Portland, Pennsylvania. Fenton and Fenton (1937) discussed the algae, and J. M. Hills (1935) found supposed arenaceous foraminifera, but they are of dubious correlative or diagnostic value. The stratigraphic position of the restricted Allentown below the Beekmantown is established; separation from the underlying Limeport formation is sometimes blurred.

LIMEPORT LIMESTONE: For the beds of Dresbachian age in the Lehigh Valley which were included by earlier authors in the Allentown formation, we proposed on an earlier page the name Limeport formation. Its fossils indicate that it is of Dresbachian, rather than of Trempealeauian age. It is well exposed at the eastern end of the Nancy Run section, along the Central Railroad of Pennsylvania tracks three-quarters of a mile northeast of the traffic bridge across the Lehigh River at Freemansburg. The contact with the Allentown is disconformable (Pl. 1, figs. 1, 2). Here, as in Bucks County, the Limeport is characterized by thick, sandy, dolomitic limestone interbedded with shaly limestone and lenses of cross-bedded sandstones. Mud cracks, ripple marks, and oölites are present, and intraformational conglomerates abundant. Algal biostromes, a conspicuous feature throughout the section, become more closely spaced toward the top.

By the above features, and by stratigraphic position, the Limeport formation can be separated in the field from the overlying Trempealeauian Allentown beds and the underlying Leithsville beds. The thickness of the Limeport formation is estimated to be 800–900 feet in the Lehigh Valley, or nearly twice as thick as in the Buckingham Valley.

LEITHSVILLE LIMESTONE: The Leithsville limestone is mostly dark, gray-blue to black, dolomitic rock, but yellowish to buff beds also occur. The whole tends to weather white or chalky. The bedding and lithologic characteristics vary as follows:

a. Thin-bedded, impure, high magnesium limestone.
b. Argillaceous, sericitic, shaly limestone to sericitic shale lacking carbonate.
c. Massive, dense, dolomitic limestone in beds up to 10 feet thick.

In small exposures or individual specimens it is difficult or impossible to identify the Leithsville, but in large exposures, particularly if they are weathered, there may be rhythmic repetition of the three variants. In weathered material the sericitic shale is conspicuous. The Leithsville rarely carries quartz sand beds, but when present they are often cross-bedded. Oölite and edgewise conglomerate are rare in contrast to the Allentown and Limeport, but ripple marks and mud cracks are plentiful.

The Leithsville beds in the Lehigh Valley are about 800–900 feet thick as compared with 400–500 feet in the Buckingham Valley. This may indicate that the Lehigh Valley area was farther out in the Upper Cambrian geosyncline than the Bucks County area. This is supported by the fact that there is Allentown in the Lehigh Valley but little or none in Buckingham Valley.

The massive phase of the Leithsville is well shown in a knoll that lies between the highway (U. S. Route No. 611) and the Delaware

River Canal and north of the eastern tip of Morgan Hill, near South Easton. Here, thick beds occur near the bottom of the section, while the higher beds show shaly and thin-bedded limestones interbedded with thicker beds. Stylolites are numerous in the higher beds, which also include a bed of calcareous, large-pebble conglomerate.

Paleontologic data, if the name Leithsville is applied as Wherry defined it, are nil. He differentiated the limestone positively from the overlying Limeport ("Allentown") on lithologic character, but negatively on the absence of "*Cryptozoa*". It appears to be stratigraphically conformable with the Limeport, but there is doubt about the precise boundary. John M. Hills (1935), in his work on the insoluble residues from the Cambrian limestones in Lehigh Valley, used the names Allentown and Leithsville, but included in the upper part of the Leithsville beds previously assigned to the Allentown both by Wherry's original definition and by Miller, although they contained a few calcareous algae. Hills drew the base of the Allentown beneath a unit in which he recognized shaly and sandy dolomite with much oölite, conglomerate and breccia, many "*Cryptozoa*" and foraminifera. He did not state how widely distributed this unit may be.

Hills's division seems artificial and not to be advised in the face of long-established usage as now recognized by the Pennsylvania Topographic and Geologic Survey, which draws the "Leithsville-Allentown" (i.e. our Leithsville-Limeport) boundary at the level of appearance of the lowest "*Cryptozoa*". Hills's evidence from insoluble residues is not necessarily conclusive. His microfossils occur in both formations and are nondiagnostic, doubtful arenaceous foraminifera. The conglomerate and breccia he mentions as marking the lowest portion of the Allentown are not confined to that horizon, but similar lithologic characteristics recur at other levels. It seems best, therefore, unless additional evidence is obtained, to continue the practice of drawing the base of the Limeport under the lowest unquestioned stromatolite (algal) zone on the evidence of the flora. This separation, which agrees with Wherry's original definition, can usually be supported by lithologic evidence observed in the field.

The Leithsville rests disconformably upon the Hardyston in the few known exposures of the contact (Whitcomb, 1948). The Leithsville ("Tomstown") has been correlated with the lower part of the Kittatinny limestone of New Jersey, which has been said (on no real evidence) to be of Early Cambrian age. Because the evidence is not convincing either as to correlation or age, it may be Early Cambrian, Medial Cambrian, Early and Medial Cambrian, or early Late Cambrian. The absence of recorded Middle Cambrian in the Lehigh Valley may be significant. Elbrook limestone of Medial Cambrian age has been reported unofficially to the southwest, in Berks County, where it is said to intervene between the Conococheague (Allentown) and the Tomstown (Leithsville).

Interrelations

Allentown Formation

The Limeport in Buckingham Valley carries two early Late Cambrian Dresbachian faunules associated with certain stromatolites. At Carpentersville, New Jersey (Howell, 1945), across the river from the Lehigh Valley, the Limeport carries an early Late Cambrian (Dresbachian) faunule, again associated with stromatolites. The Carpentersville beds are correlated with those of the lower part of the Limeport of the Lehigh Valley, Durham Creek and Buckingham Valley. No middle Upper Cambrian (Franconian) has been found in any locality in eastern Pennsylvania. Along the railroad which follows the north bank of the Lehigh River east of Nancy Run in Northampton County, one of the best Cambrian sections in eastern Pennsylvania is exposed. In the midst of this section, there is a distinct, disconformable, erosional break (Pl. 1, figs. 1, 2). There are Allentown stromatolites above and Limeport algae below. Hence, we believe that this disconformity may represent middle Late Cambrian, or Franconian, time.

The Trempealeauian Allentown age of the limestones at Portland, Pennsylvania, and at Blairstown, New Jersey, is established (Howell, 1945). Since the stromatolitic form-species *Anomalophycus compactus* Fenton and Fenton occurs at Portland within the section containing trilobites, and since a characteristic new species of *Cryptozoön* occurs with Trempeleauian

fossils at Blairstown and is probably associated with *Anomalophycus* Fenton and Fenton at Portland also, the presence of these two species in limestones elsewhere in eastern Pennsylvania is taken as evidence of the Allentown age of those limestones, since they are believed to be confined to the Allentown.

Along U. S. Highway No. 611 in the southern part of the town of Portland, Pennsylvania, Trempealeauian trilobites and brachiopods occur in the highest beds of an abandoned quarry which is also the type locality of *Anomalophycus compactus* Fenton and Fenton. Although the exact bed from which the type of *Anomalophycus compactus* came is not known, the bed was below the trilobite horizon. Behre (1927, p. 14) saw a "small form of *Cryptozoön*" in a bed near the bottom of this quarry, and noted "a very thick bed rich in a much larger *Cryptozoön*" above. Since this quarry is now filled with water, the identity of Behre's species cannot be determined, but it is likely that the small form was *Anomalophycus compactus*, which is known to occur here, and that the large form was part of the *Cryptozoön* n. sp. (referred to above) biostrome which crops out about 9 miles northeast on the Millbrook road, half a mile north of Blairstown, New Jersey.

In the Delaware River section along U. S. Highway No. 611, three-quarters of a mile southeast of the Lehigh Valley Railroad bridge in South Easton, Pennsylvania, *Anomalophycus compactus* is associated with this new species of *Cryptozoön*. The latter stromatolites form biostromes at several levels in the Allentown beds near Hope, Northampton County, Pennsylvania, and in abandoned quarries on the north, or left, bank of Durham Creek, near Durham Furnace in Bucks County. This new species of *Cryptozoön* also may be seen along Monocacy Creek between Union Boulevard and the Broad Street bridge in Bethlehem, Pennsylvania. This new species of *Cryptozoön* and another new species of *Cryptozoön* are both present in the Allentown beds of the Nancy Run section east of Freemansburg, Pennsylvania, and the latter may be seen in the Central Railroad of Pennsylvania cut west of Front Street, in Allentown.

The Allentown in Northampton County carries distinctive stromatolites associated with late Late Cambrian trilobites at Portland, Pennsylvania, and at Blairstown, New Jersey (Howell, 1945). Beds of like age are believed to occur in the Durham Valley. Consequently, the "Allentown" of the earlier workers is divisible on the basis of fossils into our restricted Allentown and new Limeport formations. The lithologic support for such a separation has been described.

Limeport Formation

The Dresbachian age of the limestones at Carpentersville, New Jersey, and at Limeport, near New Hope, Bucks County, Pennsylvania, is established. *Cryptozoön fieldii* (Fenton and Fenton) and *Archaeozoön undulatum* (Bassler) occur at the Robinson Brothers Quarry at Carpentersville, New Jersey, where Dresbachian trilobites were found. Furthermore, these same two stromatolites are present in the northern quarry at Limeport, Pennsylvania, about 180 feet above two Dresbachian faunules in the southern quarry at this settlement. Hence, the presence of *Cryptozoön fieldii* and *Archaeozoön undulatum*, on the one hand, and the complete absence of *Anomalophycus compactus* and other characteristic Trempealeauian Allentown stromatolites, on the other, are taken as evidence of the Limeport age of limestones wherever these beds contain the aforementioned *C. fieldii* and *A. undulatum*.

East of Nancy Run in Northampton County, Pennsylvania, one of the best sections of stromatolitic Limeport beds in eastern Pennsylvania is exposed. At the eastern end of this section, at least ten biostromes may be seen. *Cryptozoön fieldii* is common in the lower beds of the section, while *Archaeozoön undulatum* and *Dolatophycus expansus* are numerous in the higher beds. Westward along this same section there is a distinct, disconformable erosional break, (Pl. 1, figs. 1, 2) 15 feet above which occurs a biostrome of a new species of Trempealeauian *Cryptozoön*. Since below the break there are Dresbachian Limeport stromatolites, this disconformity may represent medial Late Cambrian, or Franconian, time.

Again, *Cryptozoön fieldii* and *Archaeozoön undulatum* are found in an old quarry in the southern part of Raubsville, Northampton County, Pennsylvania, which is in line of strike

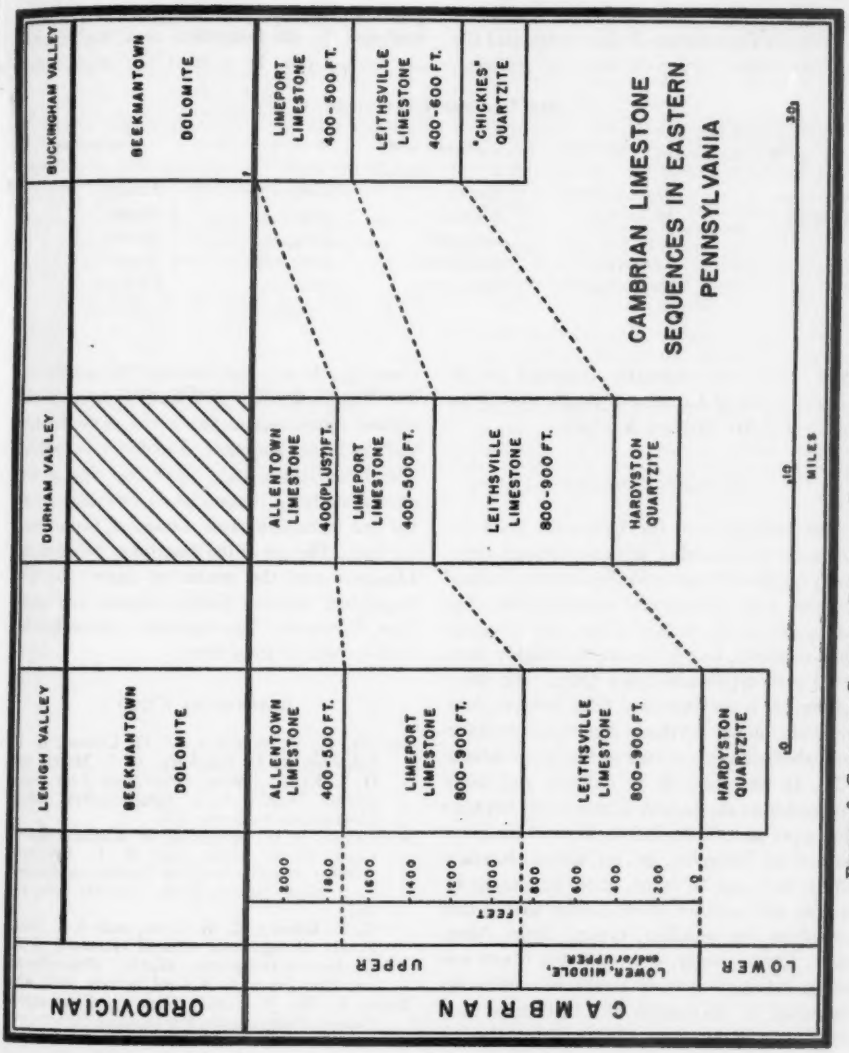


FIGURE 3. CHART OF CAMBRIAN LIMESTONE SEQUENCES IN EASTERN PENNSYLVANIA

of the Robinson Brothers Quarry across the Delaware River at Carpentersville, New Jersey. Biostromes of *C. fieldii* and *A. undulatum* occur in the Buckingham Valley at many of the localities where Limeport beds are exposed.

Valley, and the Langhorne area of eastern Pennsylvania. The equivalence of the Lower Cambrian quartzites of all four places is established. In the Langhorne area, higher beds are faulted out. In each of the other areas,

TABLE 2.—COMPARISON OF AREAS

Age	Lehigh Valley	Durham Creek	Buckingham Valley	Langhorne
Ordovician	Beekmantown	Absent	Beekmantown (?)	Absent
Cambrian	Allentown	Allentown	Absent	Absent
	Limeport	Limeport	Limeport	Absent
	Leithsville	Leithsville	Leithsville	Absent
	Hardyston	Hardyston	Chickies	Chickies
			Hellam	Hellam

These fossils are especially abundant in old quarries south of Lahaska in Bucks County on the farm of Mr. William A. Clark.

Leithsville Formation

The separation of the Leithsville from the Limeport is somewhat arbitrary, based negatively on the absence from the former of animal remains and recognizable stromatolites. The Leithsville shows certain distinctive lithologic characteristics, but it too can be roughly separated into upper and lower parts. The lower Leithsville is preëminently thick-bedded, dolomitic limestone; rhythmic recurrence of different lithologic types occurs in the upper Leithsville. In the field it is difficult and often impossible to distinguish lithologically between the upper part of the Leithsville and the lower part of the Limeport. In fact, unless abundant oölitic beds can be found, these limestones resemble one another more closely than either resembles the so-called, typical upper Allentown. Consequently, it is doubtful if any one set of lithologic criteria would be sufficiently diagnostic to distinguish the Leithsville from the Limeport unequivocally at all locations.

Table 2 shows the succession of Cambrian formations as recognized in eastern Pennsylvania areas. (*See* also Figure 3.)

CONCLUSIONS

Cambrian formations occur in the Lehigh Valley, Durham Creek Valley, Buckingham

Cambrian limestones rest on the quartzites. The Trempealeauian Late Cambrian age of the highest limestones in two areas is established and the formation name, Allentown, is applied. The Dresbachian Late Cambrian age of the next underlying limestones is established and the new formation name, Limeport, is proposed for them. The age of the limestones between the Limeport and the quartzites cannot be distinguished between Early, Medial, and early Late Cambrian. The formation name Leithsville is used for these beds.

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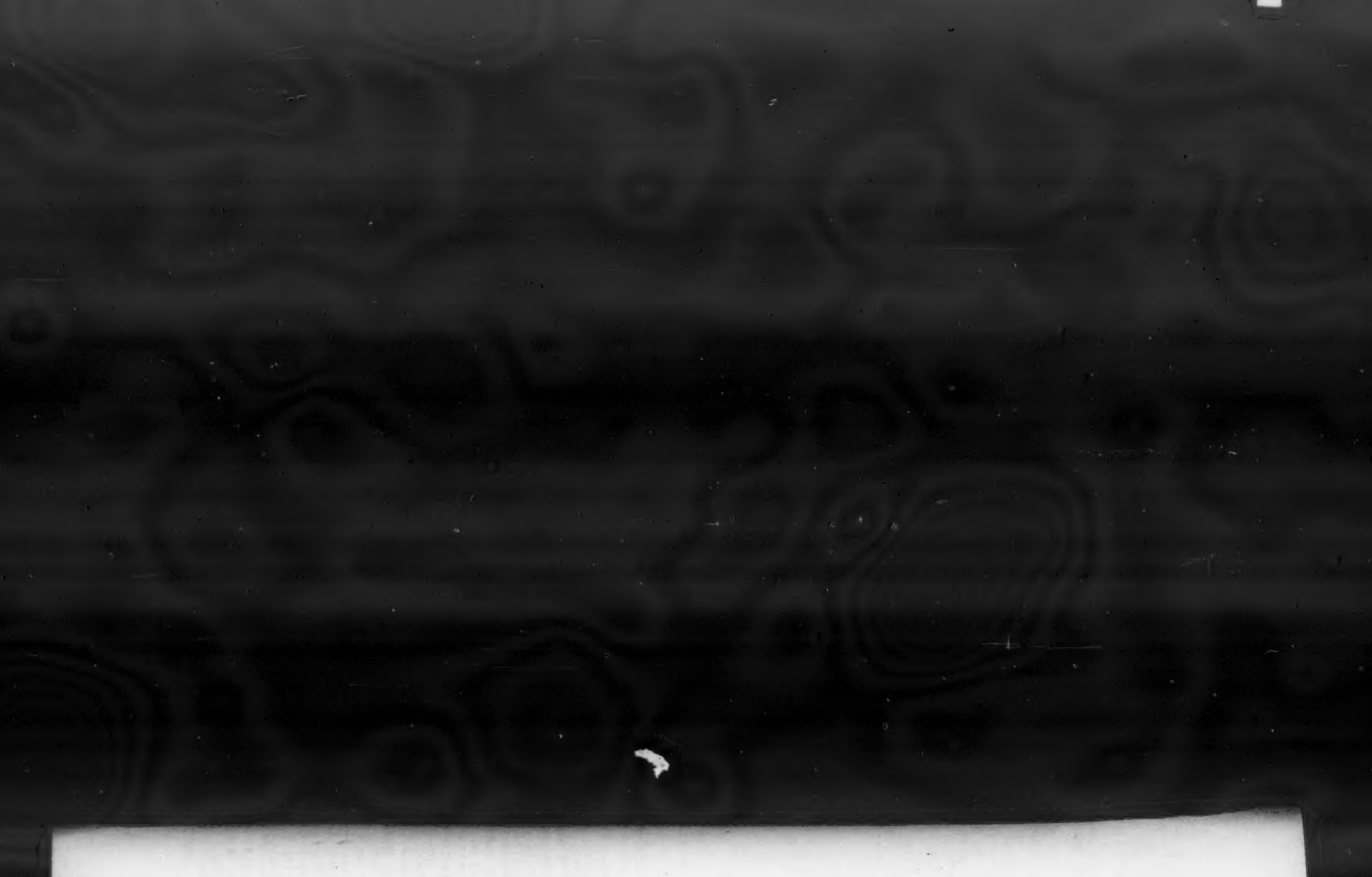
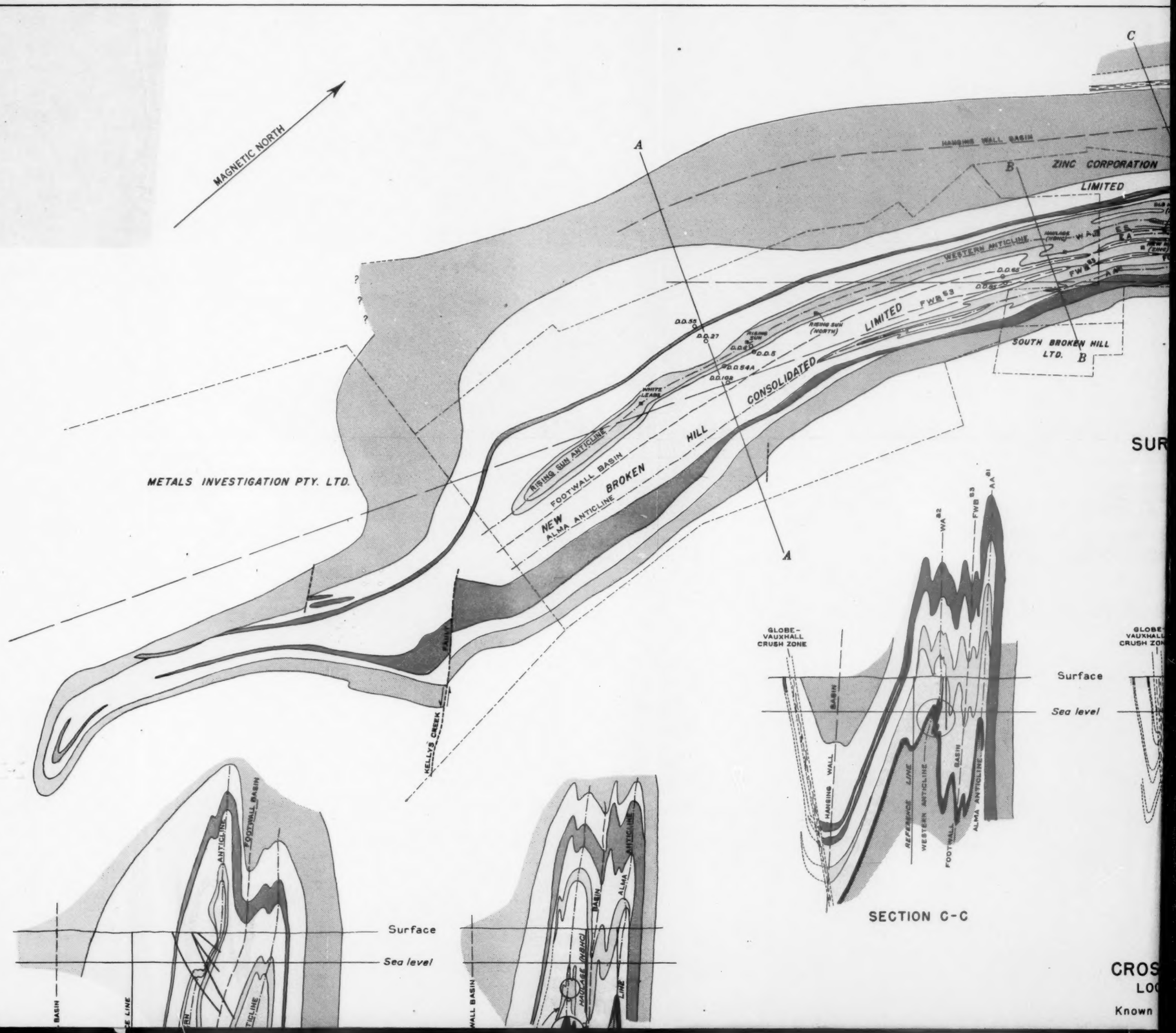


EXPLANATION

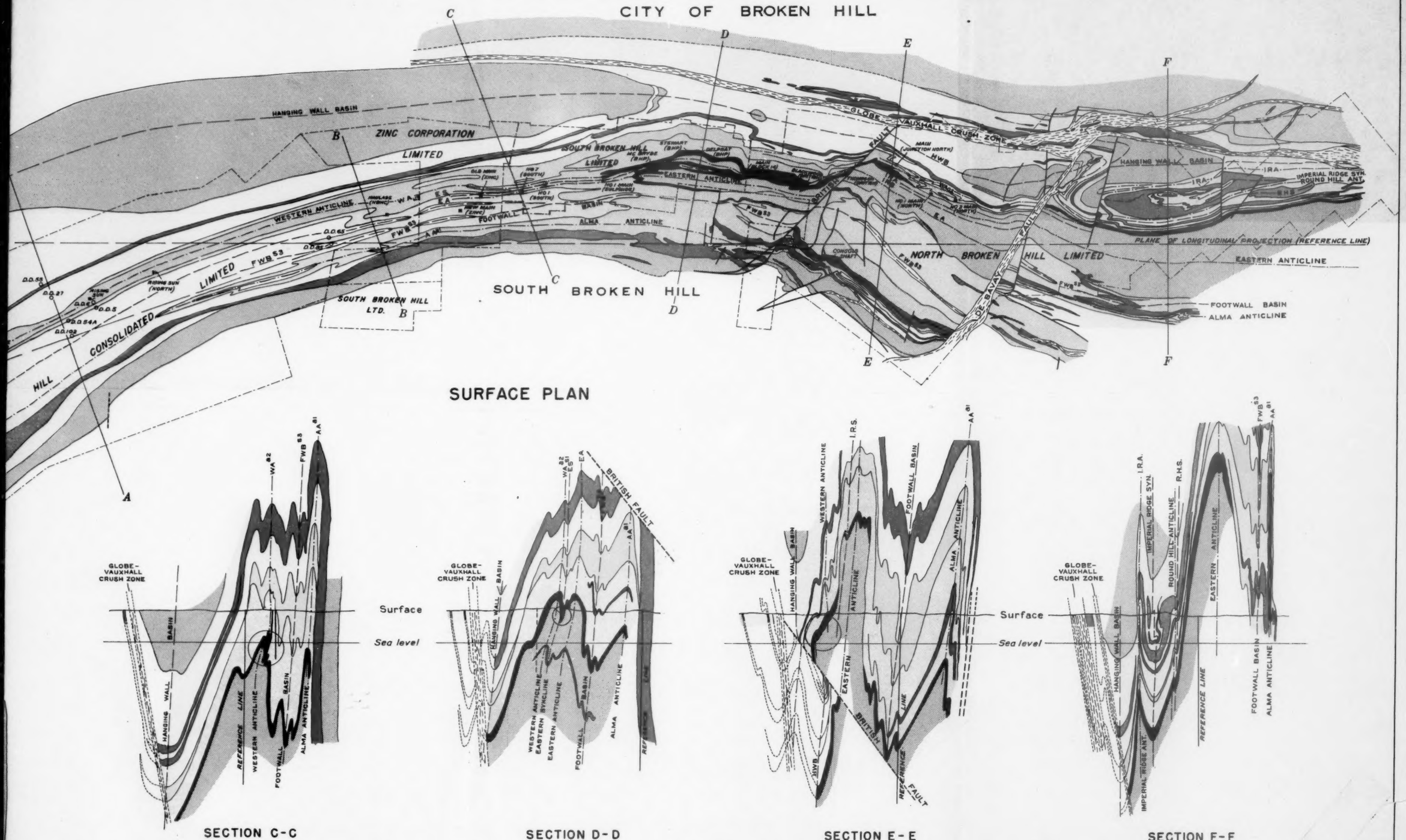
Stratigraphic Sequence of Rock Formations

		Overlying rocks undifferentiated (Sillimanite gneiss and quartzite, amphibolite sills)
	XVII	Hanging wall granite (Igneous sill)
	XVI	XVI Formation (Sillimanite-garnet gneiss)
Overwall group	XV	Town amphibolites (Igneous sills)
	XIV	XIV Formation (Sillimanite gneiss)
	XIII	Bonanza amphibolites (Igneous sills)
	XII	Potosi-Footwall gneiss (Feldspar-quartz-garnet gneiss)
Lesser zinc lode group	XI	XI Formation (Sillimanite gneiss, quartzite, galnite lodes locally)
	X	Consola amphibolites (Igneous sills)
	IX	IX Formation (Sillimanite gneiss, quartzite, zinc lodes locally)
Main zinc lode group	VIIIb	Siliceous zinc lode — Not differentiated here from VII and IX formations except on section B-B
	VIIIa	Alternating thin beds (Quartzite and gneiss) — Not differentiated here from VII and IX formations except on section B-B
	VIII	Rhodonitic zinc lode — Not differentiated here from VII and IX formations except on section B-B
	VII	VII Formation (Sillimanite gneiss and quartzite, contains locally small overwall zinc lode)
Main lead lode group	VI	No. 2 lens ore formation (Lead-silver-zinc ore locally)
	V	V Formation (Sillimanite gneiss) — Not differentiated here
	IV	No. 3 lens ore formation (Lead-silver-zinc ore locally) — Not differentiated here
	III	III Formation (Sillimanite-garnet gneiss)



CITY OF BROKEN HILL

SURFACE PLAN



SECTION C-C

SECTION D-D

SECTION E-E

SECTION F-F

CROSS SECTIONS

LOOKING NORTH

Known ore bodies in circle

(Igneous sills)

XII — Potosi-Footwall gneiss (Feldspar-quartz-garnet gneiss)

Lesser zinc lode group

XI — XI Formation (Sillimanite gneiss, quartzite, gahnite lodes locally)

X — Consols amphibolites (Igneous sills)

IX — IX Formation (Sillimanite gneiss, quartzite, zinc lodes locally)

Main zinc lode group

VIIIb — Siliceous zinc lode

VIIIa — Alternating thin beds (Quartzite and gneiss)

VIII — Rhodonitic zinc lode

Not differentiated here from VII and IX formations except on section B-B

VII — VII Formation (Sillimanite gneiss and quartzite, contains locally small overwall zinc lode)

Main lead lode group

VI — No. 2 lens ore formation (Lead-silver-zinc ore locally)

V — V Formation (Sillimanite gneiss)

IV — No. 3 lens ore formation (Lead-silver-zinc ore locally)

Not differentiated here

Underwall group

III — III Formation (Sillimanite-garnet gneiss)

II — Underwall amphibolites (Igneous sills)

I — I Formation (Sillimanite-garnet gneiss)

Faults and shear zones

Structure Lines and Symbols

Anticlinal axes

Synclinal axes

Minor folds

FWB^{S2}_{U3} — Second minor syncline from west to east in footwall basin, axial line at underwall of no. 3 lens ore formation

WA^{S2}_{O2} — Second minor anticline from west to east in western anticline, axial line at overwall of no. 2 lens ore formation

Rocks all metamorphosed sediments except where otherwise noted

Pre-folding pegmatite sills and post-folding pegmatite and uralite dolerite dykes omitted

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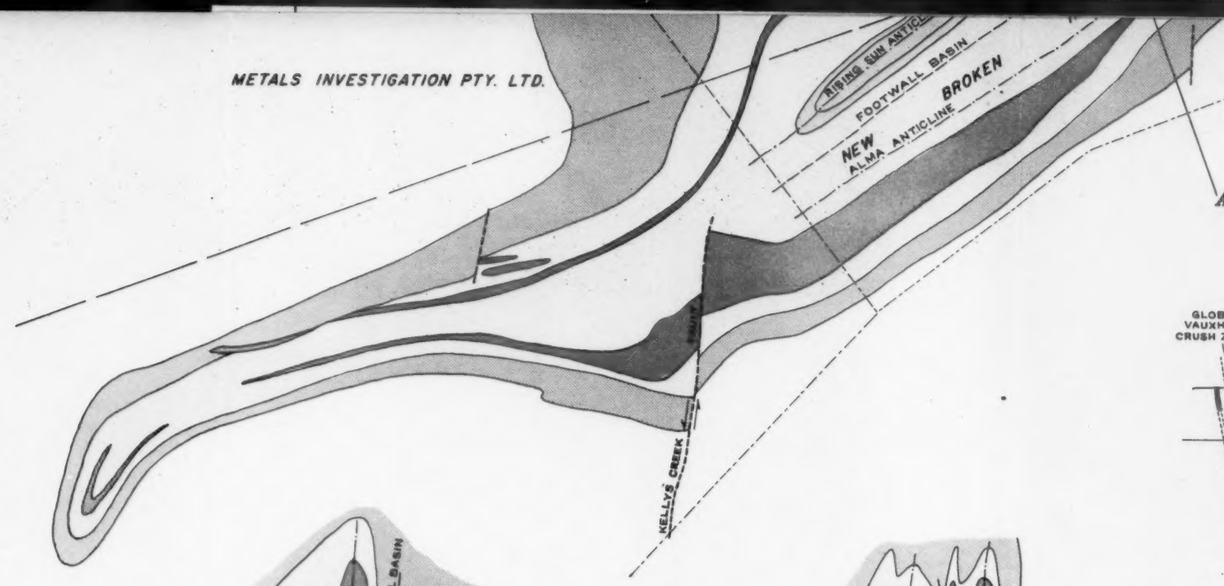
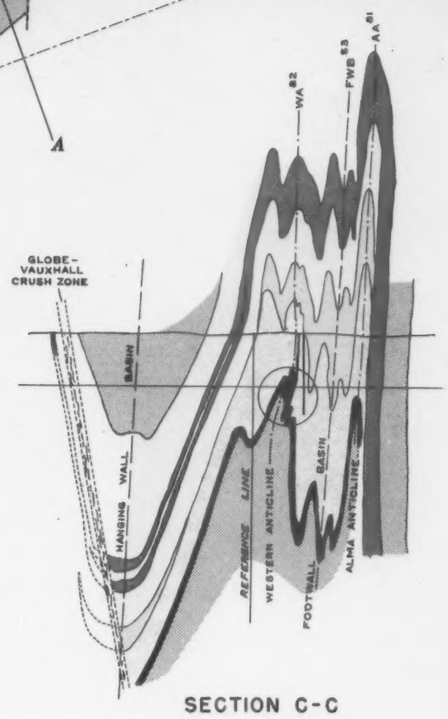
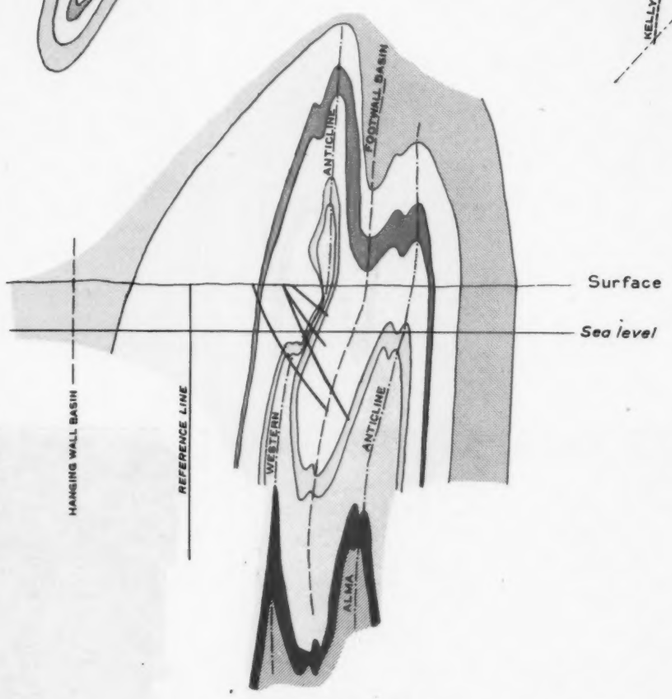
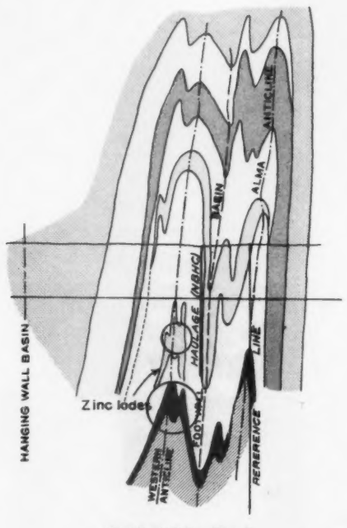




SECTION C-C



SECTION A-A



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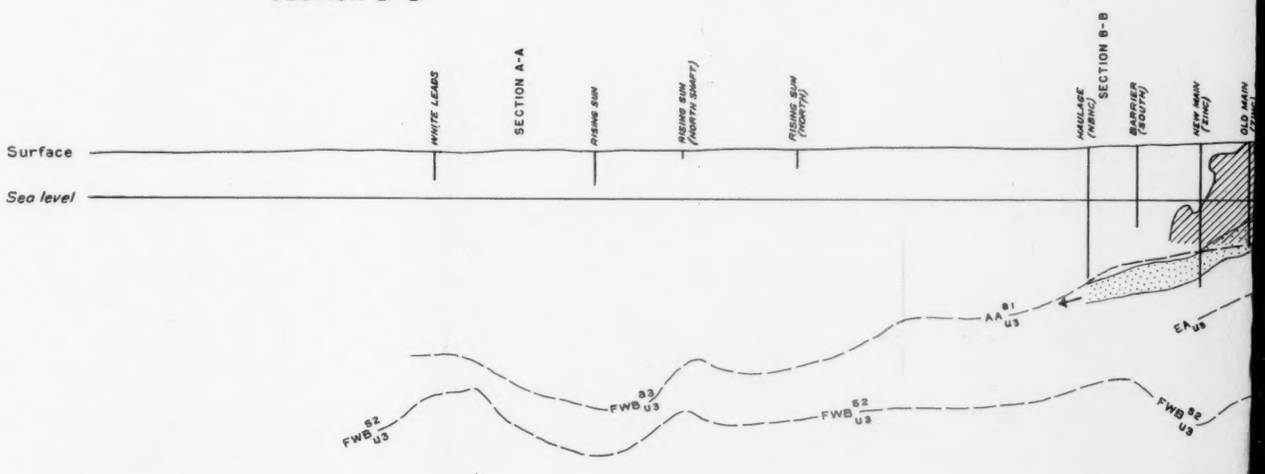


LONGITUDI
OF AXIAL LI

All axial lines
Lens ore form
overwall of N

CROS
LOC

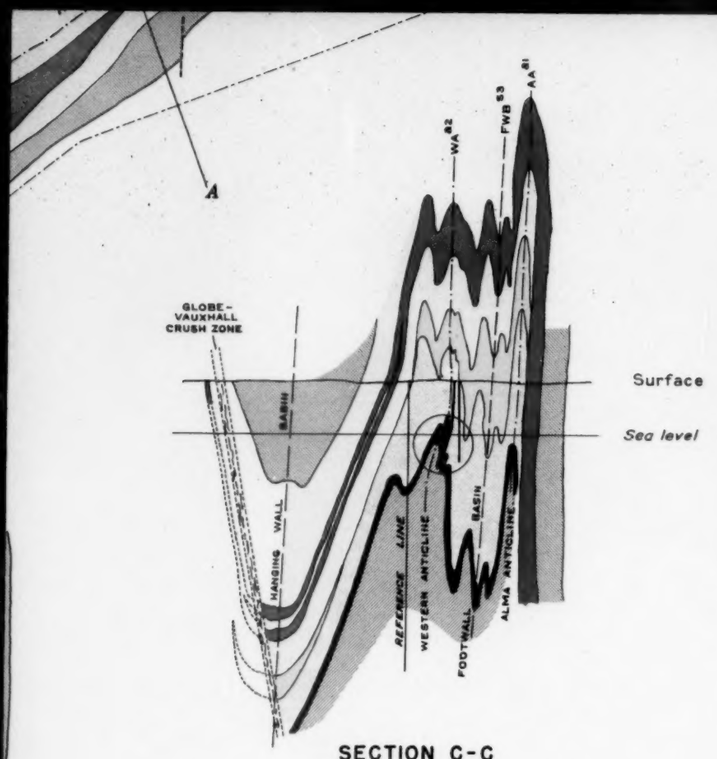
Known

GEOLOGY OF THE BROKEN HILL MINES

1000 0 5000 10000 Feet

½ 0 1 2 Mile

SURFACE PLAN



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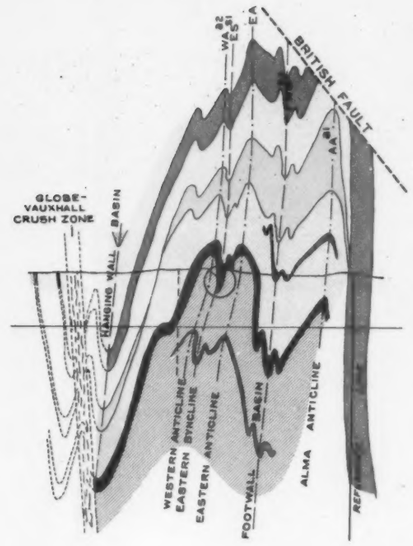

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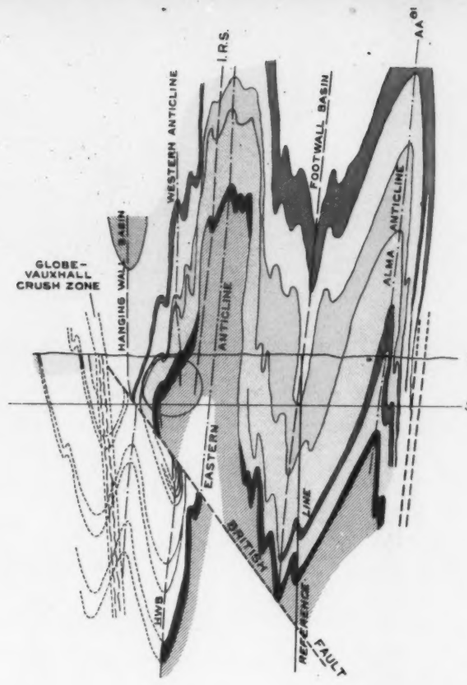

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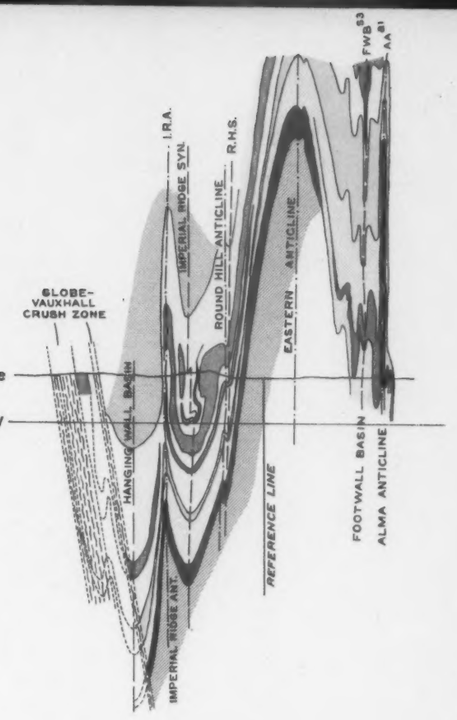
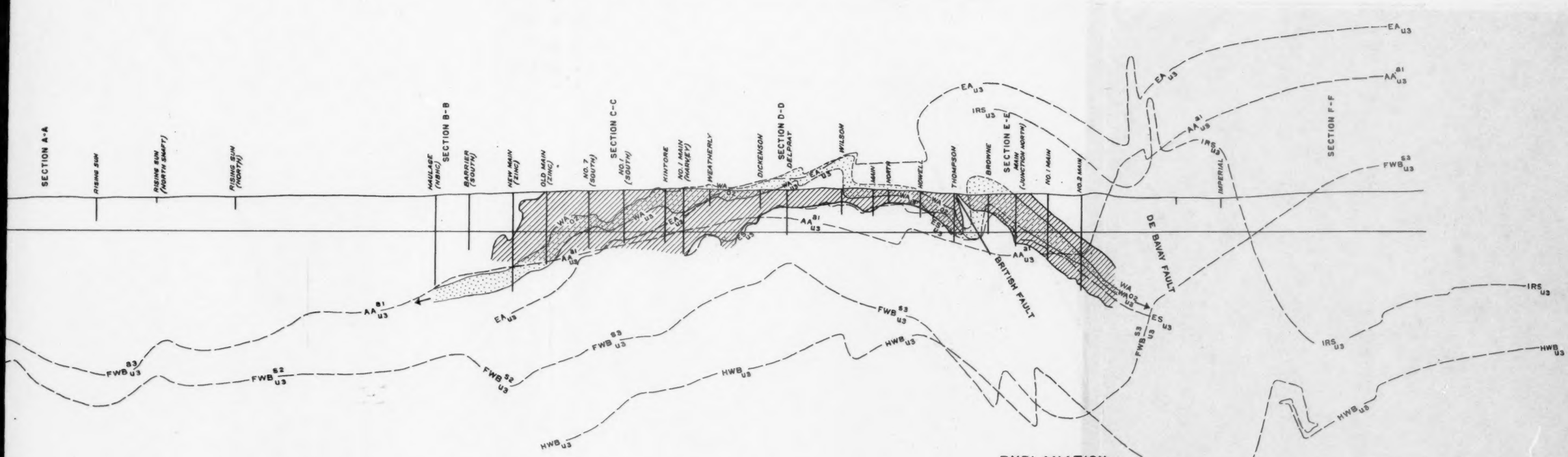


SECTION F-F

CROSS SECTIONS
LOOKING NORTH

Known ore bodies in circle



LONGITUDINAL PROJECTION
OF AXIAL LINES AND ORE BODIES

All axial lines are at underwall of No. 3 Lens ore formation, except WA_{02} at overwall of No. 2 Lens ore formation

EXPLANATION

Ore bodies stoped or developed

Locus of maximum ore in western anticline

Y OF THE BROKEN HILL MINES AREA

1000 0 5000 10000 Feet

½ 0 1 2 Miles

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GEOLOGY OF THE BROKEN HILL ORE DEPOSIT, BROKEN HILL, N.S.W., AUSTRALIA

BY J. K. GUSTAFSON, H. C. BURRELL, AND M. D. GARRETTY

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Abstract

The lead-silver-zinc ore deposit of Broken Hill, New South Wales, is among the great ore deposits of the world because of its size, richness, and continuity. Up to the end of 1946 approximately £50,000,000 in dividends had been won from recoverable metals worth £210,500,000 gross contained in 63,800,000 tons of ore. The deposit is a hypothermal deposit of Pre-cambrian age resulting from the selective replacement of two closely adjacent, tightly and complexly folded stratigraphic rock layers.

The original sedimentary rocks of the area now consist of tightly folded sillimanite-garnet gneisses with subordinate thin quartzite beds. These contain numerous folded sills of augen gneiss (granite), amphibolite (gabbro), and pegmatite. Post-folding peridotite, granite, and pegmatite occur. Probably following considerable uplift and erosion, thin dikes of diabase (dolerite) were intruded, followed by pegmatite dikes and silicifying solutions, and finally by ore-bearing solutions.

The folds of the region are tight, steeply inclined, and extremely complex structures resulting from plastic deformation. Individual minor folds were studied in great detail by a method of axial-plane and axial-line analysis. An angular relationship exists between minor and major folds due to strain under torsional stresses. The regional pitch is flatly south. However, sudden reversals of pitch and divergences of pitch in adjacent folds are common. "Second-order" folds or folded folds exist. Cutting and offsetting the folds are "buckles" with vertical axes and crush zones of schisted rocks resulting from post-folding but pre-ore faulting movements.

The lode occurs in a "belt of attenuation" between a wide arch on the west and wide basin on the east. It consists of massive lead-zinc-sulphide replacement ore bodies forming (before erosion) a long continuous, irregularly shaped, flat, curving pencil of ore, 2000–3000 feet high and 300 feet thick. In longitudinal section it describes a flat arc pitching downward at each end.

The "lead lodes" resulted from the selective replacement of two closely adjacent highly folded favorable beds. Each lode is distinguishable by its gangue mineralogy and metal ratios. No. 3 Lens (the lower) has fluoritic-rhodonitic gangue and comparatively high Zn:Pb and Ag:Pb ratios. No. 2 Lens, the upper, has calcitic gangue and comparatively low Zn:Pb and Ag:Pb ratios. At least three "zinc lodes", with similar mineralogy, occur at higher stratigraphic horizons at the south end of the field.

There is little observable zoning. Ore solutions are believed to have migrated up the regional pitch from the south. Intra-mineralization fracturing helped to localize ore shoots within favorable formations.

Introduction

Scope of this Paper

The lead-silver-zinc ore deposit of Broken Hill, N.S.W., Australia, ranks among the great ore deposits of the world because of its richness, size, and continuity. Up to the end of 1946 approximately £50,000,000 in dividends had been won from recoverable metals worth £210,500,000 gross contained in 63,800,000 tons of ore. The primary ore before erosion must have comprised at least 80,000,000 tons of practically continuously stoppable ore within a narrow belt developed 3½ miles long above a vertical depth of 3000 ft. Additional ore of average dimensions and average value is now being developed and mined from both ends of this 3½-mile belt.

This deposit is also noteworthy because of its unusual mineralogy and complex geological environment.

Although the district has been previously ably studied in a reconnaissance way and the ore deposit has been frequently mentioned in geologic literature, the Broken Hill ore bodies were mapped and studied in comprehensive detail for the first time during 1936–1939 by the Central Geological Survey. Some of the results of the Survey's work are confidential, but many scientifically noteworthy results can be discussed. This paper presents the general geology of Broken Hill as worked out by the Central Geological Survey with special emphasis on stratigraphy and structure and their control of ore deposition.

Central Geological Survey

The Central Geological Survey[1] was organized jointly by North Broken Hill Limited, Broken Hill South Limited, and The Zinc Corporation Limited primarily to appraise the possibilities of major extensions and repetitions of ore. Its work began in June 1936 and was completed in April 1939. All accessible underground workings in Broken Hill were mapped at least once, and the majority two or three

[1] Chief geologist: J. K. Gustafson; geologists: H. C. Burrell and M. D. Garretty; draftsmen: R. Miller-Randle, R. Wallace. J. R. Adam of the North Mine staff was geological assistant for a brief period at the start of the investigation.

times, on scales of 30, 40, or 60 feet to the inch. All available drill core was logged. The surface outcrops were mapped with a plane table on a scale of 100 feet to the inch using mine-triangulation systems and other mine-survey controls. Numerous old plans, ledgers, scrap books, newspaper files, and other records were searched for information about old inaccessible workings and virtually forgotten drill holes. Mapping and other data were assembled and interpreted on 100-scale and 400-scale plans and sections. The 100-scale plans of the mines area were on the average at approximately 50-foot vertical intervals; the cross sections averaged about 60 feet apart. Many longitudinal sections and special plans brought the number of finally accepted geological tracings to more than 500.

From the countless observations and interpretations recorded on these plans and sections a three-dimensional picture of one of the most contorted portions of the earth's crust was painstakingly pieced together, and the fascinating and eventful life history of a great ore deposit was read from it. Extensive exploratory diamond drilling was recommended to test various possibilities of major extensions and repetitions of ore. This exploration retarded during the war, is not yet completed.

Previous Geological Work

Excluding private reports to the mining companies, the geological literature contains at least 19 important papers on Broken Hill. These as well as other more general papers on Broken Hill are included among the 39 items of the Broken Hill bibliography listed at the end of this paper. Reports on five previous investigations warrant special attention:

(1) An able government survey and report by Jaquet in 1894.

(2) The investigation and report of the Geological Sub-committee of the Broken Hill Scientific Society in 1910.

(3) A regional consideration of age relationships and petrology of the district by Sir Douglas Mawson (1912), the first general study of the broader aspects of the field.

(4) The investigation of E. C. Andrews and his associates from 1919 to 1922 (Andrews *et al.*, 1922) which produced the first regional geologic maps as well as greatly expanded detail maps of the neighborhood of the lodes and several outlying areas. The report is a comprehensive treatise on the district with appendices on regional petrology by W. R. Browne, petrology near and in the lode by F. L. Stillwell, analyses of rocks and minerals by the mine staffs, and mineralogy by George Smith.

(5) The investigations of the mineralogy of the lodes in 1926–1927 by F. L. Stillwell, with the first microscopic study of the ore minerals.

E. C. Andrews (1922) briefly summarized most of the findings up to 1922. A paper by E. J. Kenny (1932) contains a brief summary or earlier structural concepts and a discussion of his own findings and interpretation. This paper gives a clear general picture of the lode structure and forecasts much of the general spirit of more recent findings.

Subsequent Geological Work

After completion of the Survey's work, Burrell (1942) with financial assistance from the three companies, made an exhaustive mathematical statistical analysis of metal ratios obtained from assay data and a microscopic study of Broken Hill ores. Following completion of the Survey's work, Garretty remained in Broken Hill as chief geologist of North Broken Hill Ltd. and later consulting geologist for that company and Broken Hill South Ltd. He also made an independent mineralogical study of the ores and statistical study of assay data (Garretty, 1943). Gustafson returned to Broken Hill as consultant to The Zinc Corporation Ltd. for 5 months in 1947 and during that time reviewed the new developments in geological knowledge and thought since his departure in 1939.

Since 1939, considerable new geological information has been made available as a result of mine developments in the North Broken Hill Ltd., Broken Hill South Ltd., Zinc Corporation Ltd., and New Broken Hill Consolidated Ltd. properties. These companies, and particularly the latter two under the direction of Haddon F. King, are also actively extending the area of close geological and geo-

physical investigation. Several structures postulated by the Survey and projected by it for distances of half a mile have since been drilled. Others projected for lesser distances in the mines have since been opened by drifts and cross-cuts. In gneral the results have confirmed the Survey's interpretation. Numerous small quantitative changes in mine maps and cross sections have, of course, resulted. Where these changes would affect the correctness of the reader's understanding, the illustrations accompanying this paper have been correspondingly changed. Minor changes have not been made in the other illustrations from Gustafson's report of 1939.

Acknowledgments

We are indebted to our associates Mr. J. R. Adam, the late Mr. R. G. Miller-Randle, and Mr. R. Wallace for their excellent assistance during the Central Geological Survey study, to the general managers and mine staffs for their co-operation and help throughout the investigation, to Mr. W. S. Robinson and the late Sir Colin Fraser, who personally sponsored and encouraged the work, and to their colleagues on the boards of directors of the mining companies for permission to publish this paper. The Geological Society of America financed the drafting of illustrations and typing of the manuscript and made available to The Commonwealth of Australia the tracings for use in preparing the illustrations for the Australian edition of the paper.

The splendid pioneering work of E. C. Andrews and his associates (1922) gave us a quick familiarity with the regional geology and provided many clues which led us to a surer understanding of the structure. Largely through them we benefited from the work of earlier investigators. References in the text are limited, because ours was a comprehensive and detailed study which examined the evidence anew. The countless points of agreement and disagreement between ourselves and our predecessors, are not discussed although most of the major points at issue are indicated.

A preliminary magnetic survey of the White Lead-Zinc Corporation area under the direction of J. M. Rayner in 1939 and a later more comprehensive magnetic and gravimetric survey under the direction of Oscar Weiss in 1947 were of considerable value in interpreting that region of sparse outcrops.

FIGURE 1.—MAP OF AUSTRALIA

Authorship

This paper is based on the Central Geological Survey report of 1939 (Gustafson, 1939), and at least 50 per cent of the text is taken from Vol. II of that report. Gustafson wrote all of this paper except the production data which Garretty prepared. He, however, had access to Burrell's report (1942), to parts of Garretty's thesis (1943), and to written comment by Garretty. The illustrations are all based on the 1939 Gustafson report but revised as necessary in 1947 by Gustafson for the Zinc Corporation and New Broken Hill Consolidated properties and by Garretty for the North Mine and South Mine.

THE BROKEN HILL DISTRICT

General Description

Location and physiography.—Broken Hill, a town of about 27,000 inhabitants, is at latitude 31°58′23″, longitude 141°28′10″ in New South Wales, 699 miles by rail west of Sydney and 320 miles by rail northeast of Adelaide (Fig. 2). It is in the West Darling district in the Barrier Ranges, an elongated plateau dissected into low hills rising above an extensive arid plain.

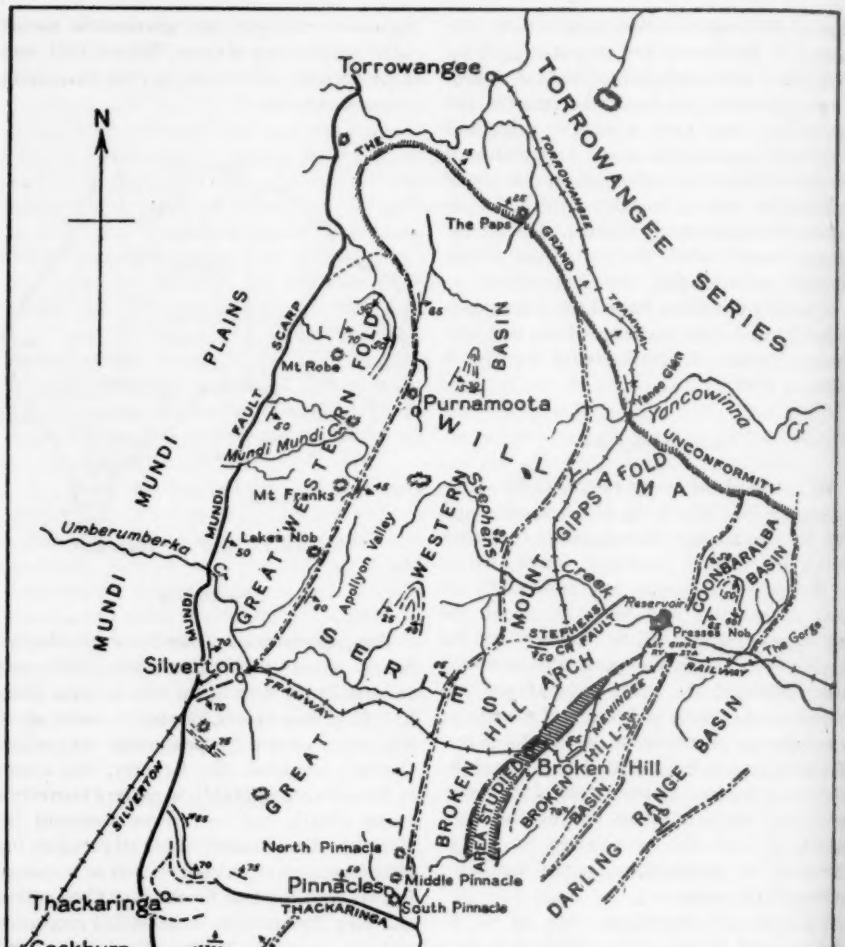

FIGURE 2.—KEY MAP TO THE PRINCIPAL GEOLOGICAL STRUCTURE OF THE DISTRICT

The lode outcrop at Broken Hill is 1000 to 1100 feet above sea level, the surrounding plain about 800 feet. The drainage is southeasterly toward the Darling River. The topography is one of late maturity.

The mines, which are contiguous, are strung along a north-south ridge rising a few tens of feet above the town of Broken Hill (Pl. 2, fig. 1).

Climate.—The climate is dry, hot in summer, and cool in winter, like much of southwestern United States. Up to the end of 1947 the average annual rainfall was 9.20 inches with maxi-

mum of 17.61 and a minimum of 2.24. The rate of evaporation is high. During the same period the lowest temperature recorded was 27.0°F. (June 30), the highest, 115.9°F. (in February). The mean minimum yearly temperature was 53.1°F., the mean maximum temperature 75.8°F. (Rainfall and temperature data from Commonwealth Meteorological Office.)

High winds and dust storms are fairly common.

Vegetation.—Various stunted forms of acacia, especially mulga, and salt bush and blue bush are characteristic, together with eucalyptus trees in the larger ephemeral creek beds. The natural scarcity of vegetation is aggravated by overgrazing by sheep and rabbits and by the cutting of wood for fuel and small mine timbers in the early days of mining.

Water.—Water for the town and mines is obtained from a reservoir at Stephen's Creek 10 miles north, and another at Umberumberka 19 miles west. During the severe drought of 1945 water was carried in by railroad cars. Under construction now is a pipeline to bring water 70 miles from the Darling River at Menindie.

History

The early history of Broken Hill (Bridges, Woodward, 1940) is a fascinating record of geological misinterpretation of a large leached ferruginous gossan which forms a prominent landmark.

The first white man to see the Broken Hill outcrop was Captain Charles Sturt who led his ill-fated expedition across the desert in a vain search for an inland sea. In 1844 Sturt sat on the Broken Hill lode outcrop to make a pencil sketch of the surrounding county. His description of "hepatic iron ore" along the spine of an isolated hill probably refers to the barren ferruginous gossan of the Broken Hill ore deposit. During a gold rush to the Barrier Ranges in 1858–1861, during which many died of thirst and privation, prospectors looking for quartz veins again passed by this great deposit. By 1866 the Mount Gipps sheep station (ranch) had been established at Stephens Creek 9 miles to the north, and the name "Broken Hill" had been conferred on a 50,000-acre paddock embracing the lode outcrop.

Rich horn silver was discovered and mined from veins at Thackaringa and Umberumberka 20 miles southwest during 1876–1880. By 1885, small but rich silver deposits had been found at Silverton, Purnamoota, and the Apollyon Valley, and Silverton for a brief time was a boom town of 3000. Broken Hill was derisively referred to as the "hill of mullock" (waste rock) and was avoided by "smart" prospectors.

On September 5, 1883, Charles Rasp, a boundary rider for the Mount Gipps sheep station, lacking both knowledge and prejudice but armed with a prospector's handbook, staked out a claim on the iron lode outcrop because it seemed to fit the description of black oxide of tin. With visions of a new Mount Bischoff tin deposit, Rasp and six associates, including McCulloch, manager of the station, staked out the whole outcrop and formed a syndicate. Early test pits encountered some lead and a little silver, but were generally discouraging. Some of the original seven sold one-fourteenth interest shares for as low as £100, shares which would have been worth millions later. The syndicate was reorganized into the Broken Hill Mining Company in 1884. Horn silver was found in a shaft in 1885. In the same year the Broken Hill Proprietary Company Limited was organized with a capital of £320,000, and shares were offered to the public. The riches of the ore deposit beneath its barren cropping were rapidly discovered and exploited. The original company was enlarged, and new companies were formed to finance the development of other blocks of ground along the outcrop.

From 1885–1898, the rich oxidized silver ores were mined chiefly by open cut and for the most part smelted locally. In 1898 the smelter was transferred to Port Pirie, S.A. From 1898 to 1915 up-to-date mining concentrating practice in the exploitation of large lead-zinc-silver sulphide ore bodies was developed and adopted. During this period lead and zinc concentrates were treated overseas. The creation in 1915 of the Broken Hill Associated Smelters Pty. Ltd., and the Electrolytic Zinc Company of Australasia Pty. Ltd. enabled the entire lead concentrate production and most of the zinc concentrate production to be treated in Australia.

By 1940, the central part of the lode had been fairly well worked out, and the old B.H.P. mine was idle. Present production comes from the north and south ends of the lode—from the properties of North Broken Hill Ltd., Broken Hill South Ltd., The Zinc Corporation Ltd., and New Broken Hill Consolidated Ltd.

Production

Entirely accurate production data are difficult to compile. Approximate figures since the commencement of operations follow:

Tons of Crude Ore mined to 31/12/1946	63,795,241
Tons of lead recovered from 1886 to 31/12/1946	8,580,226
Tons of zinc recovered from 1889 to 31/12/1946	5,194,125
Ounces of silver from 1885 to 31/12/1946	538,040,847
Ounces of gold recovered from 1893 to 31/12/1946	164,658
Total value of production to 31/12/1946	£A 210,500,000
Total dividends and bonuses paid to shareholders to 31/12/1946	£A 50,000,000
Average number of tons of ore raised per annum per man employed at present time (excluding staff)	255

Recent production figures are as follows:

Regional Geology

Rocks—Summary of Events

The rocks of the immediate district, all Precambrian, probably Archean, in age, belong to the Willyama series, a highly metamorphosed folded aggregate of sedimentary rocks intruded by several kinds of igneous rocks both before and after folding (Table 1).

The sediments originally constituted a huge thickness of monotonously similar alternating beds of clays, sandy clays, and sands. These were intruded by thick granitic sills, thinner sills of gabbro, and finally by sheets of pegmatite varying from very thin to very thick, all predominantly along bedding planes[2]. There followed a period of strong folding with a north-south-trend. It is impossible to say whether folding began before the appearance of the igneous rocks. It is certain that they experienced the major squeezing during which the sediments were converted to sillimanite gneisses, often garnetiferous, containing thin beds of quartzite; the granitic rocks became augen and "platy" gneisses; the gabbros became amphibolites and hornblende schists.

Following the main period of folding, the

[2] Possibly some of the pegmatite stringers are easily liquified portions of the gneiss "sweated" out of the rock during folding in the manner advocated by Eskola (1933).

Company	North Broken Hill Ltd.	Broken Hill South Ltd.	Zinc Corpn. Ltd.	New B.H. Cons. Ltd.	Totals
Year Ended	July 30, 1947	July 30, 1947	Dec. 31, 1946	Dec. 31, 1946	
Tons of ore milled	347,443	277,980	448,037	41,723	1,115,183
Av. Mill Head					
Grade—Pb%	14.1	12.8	14.1	7.6	
Ag. ozs	7.6	6.9	3.2	1.6	
Zn%	11.6	11.7	11.1	11.3	
Tons of Lead Conc. produced	65,881	45,650	79,313	3,851	194,695
Grade of Lead Consc.	72.5	74.7	76.9	76.7	
Tons of Zinc Conc. produced	69,215	55,431	84,631	8,221	217,498
Grade of Zinc Conc.	50.9	51.9	52.3	52.2	
Mill Recoveries					
Pg in Pb conc.	97.0	95.9	96.8	93.6	
Ag in Pb conc.	91.8	90.1	92.7	84.6	
Zn in Zn conc.	86.9	88.2	88.6	91.3	

Lead concentrate averages 0.435 lbs. of cadmium per ton of lead content.
Zinc concentrate averages 0.42 lbs. of cadmium per ton of zinc content.

TABLE 1.—SEQUENCE OF MAJOR GEOLOGIC EVENTS

	12. Uplift and erosion.
	11. Deposition of Paleozoic, Mesozoic, and Cenozoic sediments.
Upper Proterozoic	10. Deposition of Torrowangee series.
	9. Uplift and erosion.
Either lower Proterozoic or Archean	8. (c) Emplacement of lodes. Rhodonite* and "garnet sandstone"* (with attendant silicification on margins of lodes) early, followed by quartz, calcite, fluorite, and sulphides A little shearing and fracturing intervened between early and late minerals.
	(b) Post-folding shearing repeated or continued on old shears.
	(a) Intrusion of late peg matite (including green feldspar "lode" pegmatite).
	7. Intrusion of dolerite, in east-west cracks.
	6. Strong period of shearing began. Major development of crush zones, the De Bavay and British faults, puckering of the north-south folds and development of local mild east-west folds.
	5. Uplift and erosion.
Probably Archean	4. (c) Intrusion of granite aplite, pegmatite in large quantity.
	(b) Intrusion of peridotite (now serpentine).
	(a) Some development of both north-south and east-west along which granite later intruded.
	3. Period of main folding on north-south axes; regional metamorphism, possibly accompanying approach of batholith in depth.
Probably Archean	2. Intrusion of granite, gabbro, and pegmatite sills (in order named) . . . now augen and "platy" gneiss, amphibolite, and folded pegmatite.
	1. Deposition of Willyama sediments . . . now mainly sillimanite gneisses.

* Probability according to Gustafson and Garretty. Burrell considers these products of dynamic metamorphism formed during (3) with recrystallization and rearrangement during lode emplacement. Neither view is held with strong conviction.

surrounding country was invaded by irregular small intrusive masses of peridotite (now serpentine) and by bosses, dikes, and sills of granite. The granite was accompanied by some pegmatite and aplite. Neither granite nor serpentine, however, outcrops within a few miles of the line of lode. Small dikes of dolerite (diabase) followed by dikes of pegmatite and silicifying solutions entered still later, closely followed by the ore solution.

Without doubt considerable uplift and erosion followed the folding (and probably the intrusion of granite) and preceded the introduction of the thin fine-grained dolerite dikes, an apparently shallow intrusive type. Both the character of the post-dolerite rock deformation and the lode mineralogy indicate much shallower depths than the plastic deformation obtaining during folding.

Important shearing movements began sometime after folding and continued or were repeated until the period of ore deposition. Some granite, pegmatite, and aplite dikes, for example, probably followed early shears which cut across the north-south folds; yet the dikes themselves are sheared. Long narrow crush zones and faults were formed. These crush zones appear in some measure to have guided the entrance of late pegmatite and hydrothermal quartz. In a few cases, however, the pegmatite and quartz is strongly sheared by continuation or repetition of fault movements. East-west folds or "buckles" developed very locally across the dominant north-south grain of the country, probably during faulting.

Whether all these post-folding disturbances

are different manifestations of the same stresses is not yet determined. Possibly the small movements which took place after the introduction of early gangue minerals, but before the appearance of sulphides, were their last feeble expression.

Post-lode fractures in the mines cause bad ground but do not affect the understanding of the structure.

The country was uplifted following ore deposition, and some erosion ensued. The Willyama complex was covered by the glacial and fresh-water sediments of the Torrowangee (Upper Proterozoic) series, and by later Paleozoic, Mesozoic, and Cenozoic formations, all relatively undisturbed[3]. Erosion finally laid bare the Willyama series with its rich ore bodies.

Structure

Andrews (Andrews *et al*; 1922) portrays the structure between the Mundi Mundi Plains on the west and the alluvial flat beginning at Redan on the east as shallow structural, basins separated by relatively narrow arched zones of dislocation and contortion (Fig. 2). The broad basins are shown as embroidered with countless minor folds, little more than corrugations in the regional sense.

Our observations of the large Broken Hill Basin and smaller Hanging Wall Basin suggest steeply inclined structures rather than the shallow structures hypothecated by Andrews. We investigated too small an area, however, to judge whether the other structures portrayed as shallow basins may also be tightly folded.

Folding occurred under such extreme conditions of temperature and pressure that the rocks in general yielded plastically. Beds are greatly thickened on the noses of folds, greatly thinned on the limbs. Even during the later period of shearing and faulting which produced the "crush zones", the yielding action of the sediments was predominantly one of rock flowage, although the more brittle igneous rocks and the Footwall gneiss were commonly offset by rupture.

The Broken Hill line of lode is in a dominantly anticlinal portion of the zone of dislocation and tight folding between the wide Broken Hill Arch on the west and the wide Broken Hill Basin on the east. Attention is here confined almost entirely to this narrow zone of complicated structure.

Careful mapping of countless small minor folds and drag folds and the plotting of such details as mineral elongation have been an important part of the underground study. Such features give the clues to the larger structures which govern the distribution of ore bodies. In the mine area gneissosity is consistently parallel to bedding even in the noses of folds; linear elongation of light and dark mineral aggregates is conspicuous and is almost invariably parallel to axial lines (except for felted sillimanite). Elsewhere in the district where schists of a lower-grade metamorphism occur, axial-plane cleavage is highly developed.

Metamorphism

Dynamic metamorphism.—High-grade regional metamorphism characterizes the district. Originally clayey sediments were converted to garnet-biotite-cordierite-sillimanite gneiss. Calcareous sands (?) were transformed into quartz-plagioclase-garnet gneiss (Footwall gneiss). Gabbros were converted to amphibolites, commonly garnetiferous. Granites were recrystallized into augen and platy gneisses without much mineralogical change other than local development of garnet. Some originally sandy ferruginous beds are now quartz-garnet-magnetite rocks. The characteristic coarse grain and gneissic texture indicate complete recrystallization.

The almost complete plasticity obtained during folding even of thick gabbro and granite sills probably could be achieved only through profound recrystallization. Accordingly we ascribe the regional metamorphism to the period

[3] The lower beds of the Torrowangee series are somewhat deformed (Andrews, *et al.*, 1922). They contain boulders of the quartz-magnetite "lode" outcropping at "The Sisters". The garnet-magnetite-hematite "lodes" and quartz-magnetite "lodes" of the district, generally considered the same age as the lead-silver-zinc lodes, more likely are not lodes at all but original clayey iron beds converted to their present condition by regional metamorphism. Hence the relative ages of lode formation and Torrowangee sedimentation may be less definite than here assumed. No granite or pegmatite intrusives cut the Torrowangee beds (Andrews, *et al.*, 1922, p. 63) although quartz veins are present in them.

of folding and consider that the folding took place at great depth under heavy load.

Abundant contorted lenticular quartz-feldspar pegmatite stringers half an inch to several inches thick occur in many rocks, and notably in the Footwall gneiss. These stringers obviously have suffered much, if not all, of the squeezing experienced by the host rocks. They may be segregations within the rock, developed during metamorphism.

Ten miles or more from Broken Hill, staurolite and andalusite schists, chloritoid schists, and similar lower-grade metamorphis rocks prevail (Andrews *et al.*, 1922). We do not accept Andrews considered theory of a genetic as well as spatial relationship between intensity of metamorphism and intensity of ore mineralization, because we believe metamorphism occurred during folding at great depth whereas ore mineralization occurred much later at shallower depth following uplift and erosion. The localization of the higher grade of metamorphism at Broken Hill may have been caused by the presence in depth here of a buried batholith which locally contributed heat and possibly mineralizers to the rocks during metamorphism.

Contact metamorphism.—Some of the gneisses bordering the augen gneiss (Hanging Wall granite sill) and locally comprising some of the "banded gneiss" (Andrews et al., 1922) look like granitized sediments which have been dynamically metamorphosed. Little or no contact metamorphism accompanied the intrusion of the other igneous rocks, although very locally some of the gneiss adjacent to amphibolite may have been silicified and impregnated to a minor degree with dark minerals at the time of amphibolite (gabbro) intrusion.

Lode Mineralogy and Wallrock Alteration

General Character of the Lodes

The Broken Hill lodes are massive lead-zinc sulphide replacement ore bodies forming (before erosion) a long continuous, irregularly shaped, flat, curving pencil of ore roughly 2000–3000 feet high and 300 feet thick.

In longitudinal section (Fig. 3), the deposit describes a broad arc, flat in its middle (highest) portion, and pitching downward at each end.

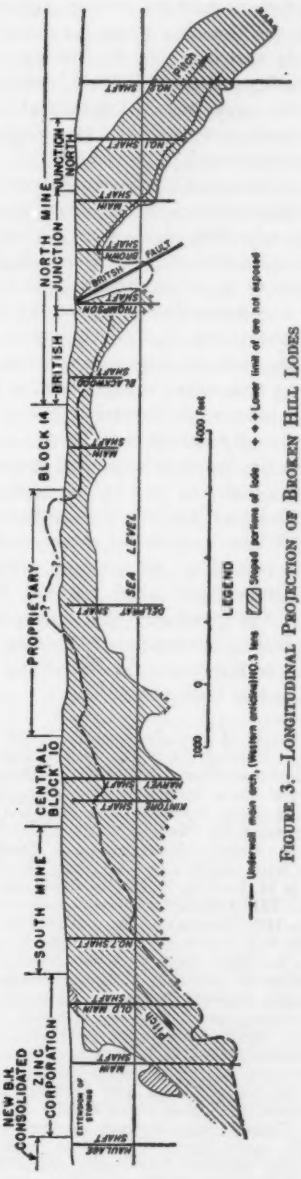

FIGURE 3.—LONGITUDINAL PROJECTION OF BROKEN HILL LODES

This arc is continuously mineralized for a horizontal distance of more than 3 miles, and except for one fault interruption between the British and Junction mines consists of continuously stoppable ore. In plan the deposit also has the appearance of an arc, though flatter than that appearing in longitudinal section. Cross sections through the lode display ore outlines representing tight folds.

One of the most significant features of the ore is that its boundaries are almost invariably parallel to bedding planes in the ancient metamorphosed sedimentary strata enclosing it; the sedimentary layers characteristically wrap around irregular projections and undulations in the outline of the ore. Looking closely at the ore in the back of a stope, one sees both small and large areas of ore in which bedding planes, usually contorted, have survived the obliterating process of mineralization. There is evidence that the ore has been introduced into an old, already folded rock and has replaced certain favorable layers of that rock, particle by particle, with large tonnages of garnet, rhodonite, fluorite, marmatite (and wurtzite), galena, and the other minerals which compose the ore bodies.[4] The possibility that rhodonite and garnet *may* be metamorphic rather than hydrothermal is discussed under "Favorable Rocks and Selective Replacement."

The ore bodies occur only where the favorable rock is intersected by a steep tabular belt of intense plastic deformation known as the "belt of attenuation".

The ores are high-grade. The average millhead grade for the three large producing companies during the 5-year period, 1934–1939, (Woodward, 1940, p. 261) was 15.0 per cent Pb, 6.34 oz. Ag, and 11.32 per cent Zn. Massive sulphide ores constitute perhaps a third of the total millfeed. Because of their composition or appearance some ores are also described as rhodonitic, fluoritic, calcitic, siliceous, zincy, steely, and/or orbicular.

Lode Mineralogy

Primary minerals.—The metallic and gangue minerals which compose the primary lodes as observed by us are[5]:

1. Abundant and conspicuous minerals:

Metallic	*Gangue*
sphalerite (marmatite)	quartz
galena	rhodonite
	garnet
	calcite
	bustamite
	hedenbergite
	fluorite
	microcline*

* Green feldspar of "lode pegmatites."

2. Metallic minerals which are widespread but generally visible only under the microscope, and gangue minerals which are locally abundant but inconspicuous, difficult to identify, or secondary:

Metallic	*Gangue*
wurtzite	pyroxmangite
pyrrhotite	johannsonite (?)
chalcopyrite	wollastonite (?)

[4] One type of lead-silver deposit in the district is very different from the main Broken Hill lodes and from most of the lesser outlying lodes. This type has a gangue of iron carbonate. The more important representatives of this type are the Purnamoota, Maybell, Lubra, Day Dream, Apollyon Valley, Silverton, and Thackaringa groups with which may be classed the Consols group in M. Ls. 234, 97, and 98 east of the North Broken Hill Limited property (Andrews *et al.*, 1922, p. 169). They are all characterized by haloids of silver in a quartz ironstone gangue in the oxidized zone. The Consols mine also contained small quantities of smaltite, cobaltite, chalcopyrite, pyrrhotite, arsenopyrite, pyrite, native antimony, molybdenite, and a few less common minerals, (George Smith, Andrews, *et al.*, 1922, Appendix IV). Although the Thackaringa lodes appear to be replacements of folded beds (Jacquet, 1894, p. 112), the Consols lodes, and probably many of the others, are veins which occupy faults. The main Consols lode occupies a fault striking N86½W, and dipping 30°–35° S, which cuts across and displaces amphibolite and gneiss. The great difference in both mode of occurrence and in mineralogy suggests that these lodes, although possibly not genetically unrelated to the main Broken Hill lodes, may represent a separate period of mineralization under different conditions of temperature and pressure, and of chemical composition of ore solutions. The siderite veins are mesothermal, the main Broken Hill lodes hypothermal. Andrews, *et al.*, 1922 (page 190) considers the siderite veins younger on evidence outside the area studied by us. Small platinoid lodes with cobalt, nickel, and copper associated with serpentine and small tin-wolfram deposits in the late pegmatites also occur but not in the area covered by this report. (Andrews, *et al.*, 1922.)

[5] Stillwell (1926, 1927) also reports argentite, berthierite, bornite chalcocite, stromeyerite, and willyamite,

Metallic	*Gangue*
marcasite	manganocalcite
tetrahedrite	rhodochrosite†
cubanite	
dyscrasite	
pyrargyrite	
gold	

3. Metallic minerals of local occurrence which generally can be seen only under the microscope, and rare and accessory gangue minerals which, in most cases, can be seen only under the microscope:

Metallic	*Gangue*
löllingite	graphite
arsenopyrite	apatite
X-mineral	titanite
pyrite	olivine (?)
bournonite	iddingsite (?)†
magnetite	micas
niccolite	basaltic hornblende (?)
molybdenite	sturtite†
gahnite	kaolin†
wolframite	tourmaline
scheelite	
cobaltite	
meneghinite	
goethite†	
covellite†	

† May be entirely supergene.

PARAGENESIS: Burrell's microscopic study suggested the following order of depostion of metallic minerals, with considerable overlapping: löllingite, arsenopyrite, pyrite, pyrrhotite, sphalerite, tetrahedrite, chalcopyrite, bournonite, galena, pyrargyrite, wurtzite, and marcasite, with the last three possibly supergene. Garretty concluded that the major sequence of mineral precipitation, with considerable overlapping, was: magnetite, pyrite, löllingite, arsenopyrite, molybdenite, wolframite, scheelite, cobaltite, pyrrhotite, chalcopyrite, marmatite, tetrahedrite (i), bournonite, dyscrasite and galena, tetrahedrite (ii), pyrargyrite, and gold.

Our difference of opinion and doubt as to the probable origin and sequence of deposition of some of the gangue minerals, is discussed under "Favorable Rocks and Selective Replacement".

Table 2 summarizes the diagnostic mineral criteria for each major ore horizon and its ore type.

Secondary minerals.—The near-surface oxidized ores have long since been mined out, and consequently were not studied by us. The extensive assemblage of secondary minerals in the oxidized zone has for the most part been abundantly described by others (Smith (Andrews *et al.*, 1922), the Geological Sub-Committee (1910), E. C. Andrews (Andrews *et al.*, 1922) and F. L. Stillwell (1927)). There was great silver enrichment and zinc impoverishment near the surface with a local thin zone of secondary chalcocite just above the primary sulphides. Oxidation and secondary enrichment are particularly well described by the Geological Sub-Committee (1910).

Open solution cavities, cellular "boxworks", and other signs of local oxidation occur in the mines on the deepest levels more than 2600 feet below the pre-mine water level. The occurrence of a soft gray zinc-rich material, covellite, and limonite in microscopic cracks in the ores and the presence of pyrargyrite, marcasite, and wurtzite are microscopic evidence of deep supergene activity. It is difficult or impossible always to distinguish between deep natural oxidation and post-mine oxidation resulting from artificial lowering of the water table. Gustafson is inclined to agree with Garretty and Blanchard (1942) that virtually all the deep oxidation is post-mine. Burrell thinks most of it may be natural oxidation during a former arid period of low water table. (Andrews et al., 1922, p. 29) hints at other evidence for such a period.

Metal ratio studies let Burrell and Garretty to different conclusions regarding the depth of secondary enrichment of silver. Burrell concluded that deep local supergene enrichment of silver is well demonstrated by variation of the silver-lead ratio in the B. H. P. mine. Garretty, on the other hand, believes that variation of the silver-lead ratio in the "main shear" syncline of the B. H. P. mine is directly related to structure; that in the North Mine there is no significant variation in the silver-lead ratio with depth; but that the silver-lead ratio is systematically somewhat higher in synclines and lower in anticlines, because fracturing late in the paragenetic sequence when silver minerals were being deposited was more prevalent in synclines. Garretty regards the

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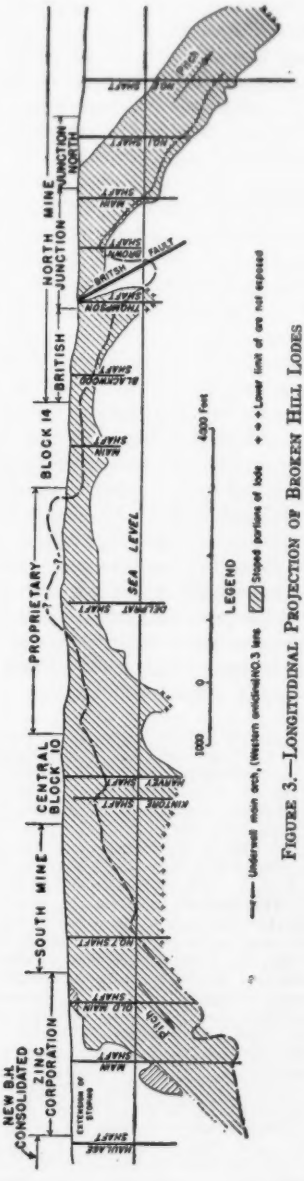

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bournonite	iddingsite (?)†
magnetite	micas
niccolite	basaltic hornblende (?)
molybdenite	sturtite†
gahnite	kaolin†
wolframite	tourmaline
scheelite	
cobaltite	
meneghinite	
goethite†	
covellite†	

†May be entirely supergene.

PARAGENESIS: Burrell's microscopic study suggested the following order of depostion of metallic minerals, with considerable overlapping: löllingite, arsenopyrite, pyrite, pyrrhotite, sphalerite, tetrahedrite, chalcopyrite, bournonite, galena, pyrargyrite, wurtzite, and marcasite, with the last three possibly supergene. Garretty concluded that the major sequence of mineral precipitation, with considerable overlapping, was: magnetite, pyrite, löllingite, arsenopyrite, molybdenite, wolframite, scheelite, cobaltite, pyrrhotite, chalcopyrite, marmatite, tetrahedrite (i), bournonite, dyscrasite and galena, tetrahedrite (ii), pyrargyrite, and gold.

Our difference of opinion and doubt as to the probable origin and sequence of deposition of some of the gangue minerals, is discussed under "Favorable Rocks and Selective Replacement".

Table 2 summarizes the diagnostic mineral criteria for each major ore horizon and its ore type.

Secondary minerals.—The near-surface oxidized ores have long since been mined out, and consequently were not studied by us. The extensive assemblage of secondary minerals in the oxidized zone has for the most part been abundantly described by others (Smith (Andrews *et al.*, 1922), the Geological Sub-Committee (1910), E. C. Andrews (Andrews *et al.*, 1922) and F. L. Stillwell (1927)). There was great silver enrichment and zinc impoverishment near the surface with a local thin zone of secondary chalcocite just above the primary sulphides. Oxidation and secondary enrichment are particularly well described by the Geological Sub-Committee (1910).

Open solution cavities, cellular "boxworks", and other signs of local oxidation occur in the mines on the deepest levels more than 2600 feet below the pre-mine water level. The occurrence of a soft gray zinc-rich material, covellite, and limonite in microscopic cracks in the ores and the presence of pyrargyrite, marcasite, and wurtzite are microscopic evidence of deep supergene activity. It is difficult or impossible always to distinguish between deep natural oxidation and post-mine oxidation resulting from artificial lowering of the water table. Gustafson is inclined to agree with Garretty and Blanchard (1942) that virtually all the deep oxidation is post-mine. Burrell thinks most of it may be natural oxidation during a former arid period of low water table. (Andrews et al., 1922, p. 29) hints at other evidence for such a period.

Metal ratio studies let Burrell and Garretty to different conclusions regarding the depth of secondary enrichment of silver. Burrell concluded that deep local supergene enrichment of silver is well demonstrated by variation of the silver-lead ratio in the B. H. P. mine. Garretty, on the other hand, believes that variation of the silver-lead ratio in the "main shear" syncline of the B. H. P. mine is directly related to structure; that in the North Mine there is no significant variation in the silver-lead ratio with depth; but that the silver-lead ratio is systematically somewhat higher in synclines and lower in anticlines, because fracturing late in the paragenetic sequence when silver minerals were being deposited was more prevalent in synclines. Garretty regards the

TABLE 2.—SUMMARY OF DIAGNOSTIC CRITERIA FOR EACH MAJOR ORE HORIZON AND ITS ORE TYPE*
Modified after Burrell (1942)

Mineral	No. 2 Lens	No. 3 Lens
CALCITE	common to abundant STRONGLY INDICATIVE	Rare
FLUORITE	sporadic to rare	common INDICATIVE
GARNET with index of refraction less than 1.794	common typical possibly highly diagnostic	present not diagnostic*
GARNET with index of refraction between 1.794 & 1.7945	present not diagnostic*	present not diagnostic*
GARNET with index of refraction greater than 1.795	absent†	present TYPICAL part of index range
RHODONITE with beta index of refraction less than 1.730	common HIGHLY DIAGNOSTIC	absent
RHODONITE with beta index of refraction greater than 1.74	absent	common to abundant HIGHLY DIAGNOSTIC
PYROXMANGITE with beta index of refraction greater than 1.74	absent	local HIGHLY DIAGNOSTIC
PYROXMANGITE with beta index of refraction between 1.738 & 1.74	not identified but possible*	not identified but possible*
PYROXMANGITE with beta index of refraction less than 1.738	not identified but possible†	not identified but unlikely to be found
BUSTAMITE	common HIGHLY DIAGNOSTIC	absent
WOLLASTONITE	rare except south end HIGHLY DIAGNOSTIC	absent
JOHANNSENITE	probably present	absent
HEDENBERGITE with beta index of refraction less than 1.740	sporadic HIGHLY DIAGNOSTIC	absent (?)
HEDENBERGITE with beta index of refraction greater than 1.740	possible*	possible*

* Further field work and laboratory tests might clarify whether this mineral might be highly diagnostic in any portion of the indicated range in refractive index.

† Further field work and laboratory tests should check this point.

absence of demonstrable supergene rearrangement of metals in the northern ore body of the North Mine which has been notably affected by deep oxidation as evidence that deep supergene enrichment is unlikely in the B. H. P. Mine. Gustafson believes that the statistical and mineralogical evidence does not conclusively show that either secondary silver enrichment or a structural control of hypogene silver distribution is solely responsible for the distribution of silver-lead ratios.

Wallrock Alteration

In general, wallrock alteration is neither intense nor extensive. It is not uncommon to find ore enclosed by but slightly altered gneiss. The most widespread wallrock alteration is silicification; where intense, it converts all gneisses to fine-grained "quartzite". Garnetization occurs also rather abundantly but seldom reaches very far beyond the lodes. Many of the "quartzites", especially where metallized, are

impregnated with very fine-grained garnet and are noted as lavender or brown "garnet quartzite". Often seen in stopes is an alteration product termed "garnet sandstone", consisting almost entirely of small garnet grains poorly cemented by quartz. There are all gradations between "garnet sandstone" and "garnet quartzite" and between "garnet quartzite" and relatively unaltered sillimanite gneiss.

Slightly altered gneiss in the walls of the lode is generally bleached, the biotite and sillimanite having been changed to sericite. Large garnet porphyroblasts have also been destroyed in the gneiss near ore (*See* Andrews *et al.*, 1922, p. 390).

By far the most extensive hydrothermal alteration in the district is in and close to the zinc lodes above No. 2 Lens Formation in the Zinc Corporation and New Broken Hill Consolidated mines where fine-grained silicification and garnetization occur on a comparatively large scale accompanied by rather disperse sulphide mineralization.

Metal Ratios

During 1936-1938 the Zinc Corporation systematically sampled its stopes, and Burrell, then mine geologist, mapped ore types. Burrell and C. P. Boundy made a statistical study of assay data to determine the metal ratios and their possible meaning in terms of zoning, recognizable ore horizons, secondary enrichment, and related problems.

Before, analysis assays had been cut by arbitrary mine conventions to 10 per cent Pb, 10 oz. Ag, 15 per cent Zn. Many hundreds of samples were plotted on a pair of "scatter diagrams", one with Pb on the abcissa and Ag on the ordinate. The resulting cloud of points was obviously crudely clustered about two axes on each diagram. The majority of the points clustered about one axis were derived from fluoritic ore, whereas most of the points clustered about the other axis were derived from calcitic ore.

Next, "class mean graphs" were constructed to obtain clearer definition of the axes mentioned above. Treating the two ore types separately, all samples were classified into 2 per cent Pb classes—0 to 2 to 4 per cent etc. The average Pb, Ag, and An content of each class was calculated, and the resulting points for each ore type plotted and joined. (Figs. 4 and 5).

Gustafson, mapping in the South Mine, had decided on structural grounds that the ore was divisible into two, or possibly three, folded stratigraphic horizons. With minor adjustments

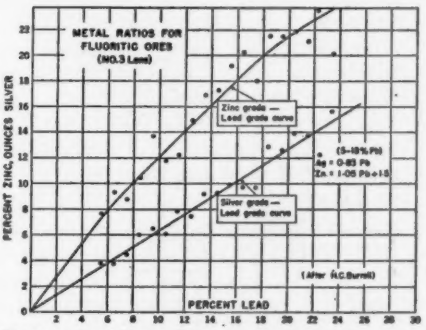
METAL RATIOS FOR FLUORITIC ORES (NO.3 Lens)
PERCENT ZINC, OUNCES SILVER
PERCENT LEAD
Zinc grade — Lead grade curve
Silver grade — Lead grade curve
(After H.C.Burrell)

FIGURE 4.—METAL RATIOS FOR FLUORITIC ORES (NO. 3 LENS)

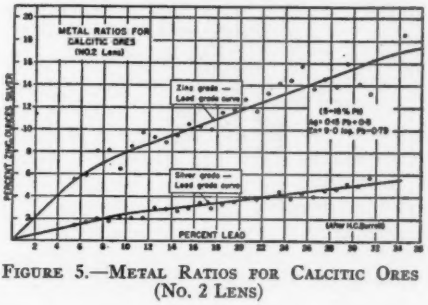
METAL RATIOS FOR CALCITIC ORES (NO.2 Lens)
PERCENT ZINC, OUNCES SILVER
PERCENT LEAD
Zinc grade — Lead grade curve
Silver grade — Lead grade curve
(After H.C.Burrell)

FIGURE 5.—METAL RATIOS FOR CALCITIC ORES (NO. 2 LENS)

in the interpretation it was possible to show that the fluoritic type of ore with its characteristic metal ratios corresponded to one ore horizon and the calcitic type of ore corresponded to another (or as then thought to two others). The distinction between high-lead calcitic ore and high-zinc "silicate gangue" ore was early recognized by the Geological Sub-Committee (1910), but not the stratigraphic significance of these ore types.

Eventually the metal ratios so obtained were found to be essentially valid for the entire line of lode; they were successfully used to distinguish ore types and work out structure in old worked-out inaccessible portions of the mines.

Burrell and to a lesser degree Garretty have

carried out further comprehensive statistical studies of the Broken Hill assay data, the results of which will be published later.

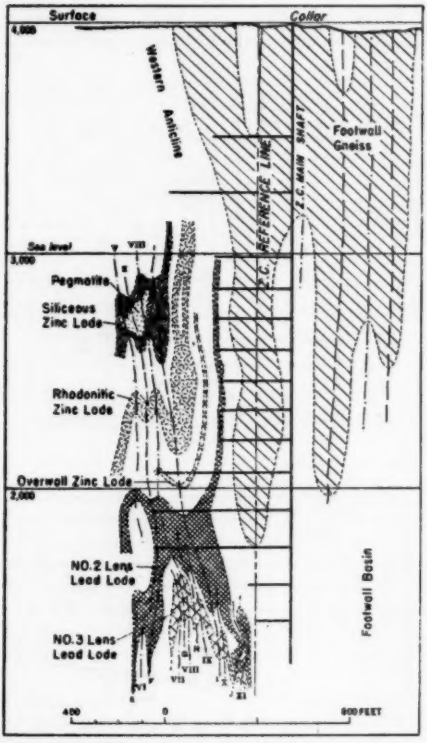

FIGURE 6.—CROSS SECTION 30, ZINC CORPORATION MINE

Folded Ore Horizons

General statement.—The first fact of major importance in understanding Broken Hill ore bodies is that they were formed by the selective replacement of closely adjacent favorable stratigraphic rock layers which have been closely folded.

All the steep tabular ore replacing the shear zone known as the "main shear" was at first called "shear ore", but most of it was later identified as replacing favorable rock formations where they are involved in the shear. There remains very little such "shear ore" which cannot be identified as belonging to recognized favorable rock formations; such ore occurs chiefly above the "broad lodes" in the Zinc Corporation and South Mine. "Shear ore" will be used here to distinguish the steep, narrow, tabular ore above or below the "broad lodes" even though it has been recognized as an attenuated fold (or limb of a fold) of a favorable rock formation and has been so designated on the plans and sections.

Stratigraphic position is but one of several requirements for an ore body. Others will be dealt with in the discussion of structure.

The two favorable beds which have contributed virtually all of Broken Hill's ore are known as the No. 2 Lens ore formation (upper) and No. 3 Lens ore formation (lower) (Fig. 6). The No. 2 Lens and No. 3 Lens ore bodies are usually readily distinguishable. Each possesses its own characteristic assortment of gangue minerals and its own distinguishing metal ratios.

The Central Geological Survey recognized a third formation, the No. 1 Lens formation overlying No. 2 Lens formation in the Zinc Corporation Mine. A new structural analysis of Zinc Corporation data in 1947 by Gustafson and King proved that there are only two lead ore horizons, a situation suspected by Burrell 1942, (p. 21, 231, 435) as a result of mineralogical and statistical study.

There are also other rock layers in the district stratigraphically above these which have been mineralized but which have never yielded much ore. They are discussed under "Zinc Lodes".

The relative positions of the lodes are shown in Figure 6.

No. 3 Lens ore formation.—This lowest ore horizon has produced approximately 50 per cent of the ore and the richest ore in Broken Hill. It is continuously mineralized from where it is exposed in the Zinc Corporation mine northward to the British fault. This same folded formation gave the Junction, Junction North, and North mines their southern or lower ore body on the other side of the British fault. In most of the mines the No. 3 Lens ore bodies are bigger than the No. 2 Lens ore bodies. In the South Mine near the Zinc Corporation boundary, however, the No. 2 Lens ore bodies are considerably larger. Where the No. 3 Lens ore is being developed in the Zinc Corporation, moreover, it appears that this increase in size of the No. 2

Lens ore bodies is accompanied by a marked diminution in size of the No 3 Lens ore bodies.

The primary metallic minerals[6] are: sphalerite slightly in excess of galena; extremely subordinate pyrite, löllingite, and (locally massive) pyrrhotite; and rare chalcopyrite. Large stope areas consist of massive sulphides with a small percentage of gangue. The gangue minerals are: occasionally conspicuous fluorite, usually disseminated but also in patches; fine- to medium-grained "rhodonite"; sugary quartz; garnet; and very rare calcite[7]. Large masses of almost pure rhodonite occupy more than 50 per cent of the cross-sectional area of No. 3 Lens in portions of the Block 14 and British mines, although in the other mines it more often occurs disseminated through the sulphides or as small partly replaced patches in the sulphides.

"Garnet sandstone" is commonly developed on the margins of the lode, especially on the underwall side. Poorer portions of the ore body may consist of scattered sulphides or small seams of sulphides in highly silicified rock ('quartzite'). Green feldspar is sometimes seen in "lode pegmatite".

Metal ratios are shown in Figure 4. Typical medium to high-grade ore assays 18 per cent Pb, 11.5 oz. Ag, 20 per cent Zn. In the ore-bearing folds, probably 80 per cent of this formation was replaced by ore over a strike (pitch) length of 3½ miles.

No. 2 Lens ore formation.—This middle horizon is responsible for about half of Broken Hill's ore. It has furnished important ore in the Zinc Corporation, South Mine, British Mine, North Mine, and in the Broken Hill Proprietary open cut. A few stopes exist in it in the south end of the Central Mine. Most of it has been eroded in Block 14 and the Junction mine. Except at the south end of the line of lode, mineralization is generally more erratic and less intense than in No. 3 Lens. Nevertheless probably 80 per cent of the formation in the ore-bearing folds was replaced by mineable ore for a distance of 3½ miles.

The metallic minerals are: galena, somewhat predominant over sphalerite; very subordinate chalcopyrite; pyrrhotite; pyrite (especially on the overwall side in Zinc Corporation). Sulphides seldom constitute more than 50 per cent of many large stope areas. The gangue minerals are abundant calcite and/or quartz; local small patches of coarse-grained massive "rhodonite"; occasional "hedenbergite"; rare fluorite (usually green or white, seldom red or brown); and garnet. "Garnet sandstone" is usually less abundantly developed on the margins than is the case with No. 3 Lens. Lean ore as in No. 3 Lens usually consists of poorly mineralized "quartzite". Green microcline pegmatite occurs in some stopes. Metal ratios are shown in Figure 5.

This description applies to the No. 2 Lens occurrences north of the Zinc Corporation Mine and in the Zinc Corporation Mine above the 12 level. The lower levels of that mine, however, reveal a change in the mineralogy of No. 2 Lens. "Rhodonite" exceeds calcite over large stope areas, and very low-grade portions of the ore body, tens of feet wide, are composed almost entirely of "rhodonite", although the "rhodonite" retains the Ca-Mn-Fe ratio diagnostic of No. 2 Lens. "Hedenbergite" ("green rhodonite") is also prominently developed in many of these areas, especially along the east margin of the ore body and along the underwall. "White rhodonite" or "wollastonite" (possibly all bustamite), rarely seen heretofore, is the chief constituent of some low-grade areas of No. 2 Lens ore on the 18 level of the New Broken Hill Consolidated Mine in the nose of the Western anticline. Except for conspicuous amounts of calcite and general higher galena-sphalerite ratios for such sulphide mineralization as exists, these low-grade or barren rhodonite areas closely resemble the rhodonite areas in No. 3 Lens in the old British Mine. Another change is the local occurrence of conspicuous pink fluorite crystals encased in calcite in No. 2 Lens ore.

There is some suggestion in low-grade portions of the ore body of a greater prevalence of high zinc-low silver assay values. These resemble No. 3 Lens or zinc lode ratios for lead and

[6] Unless otherwise noted, only those minerals are considered which can ordinarily be seen with the naked eye. See Andrews, *et al.*, (1922), Stillwell (1926) for a fuller discussion of mineralogy. "Rhodonite" henceforth refers to any of the pink minerals of the rhodonite group (rhodonite, pyroxmangite, bustamite). "Hedenbergite" refers to the green minerals (hedenbergite and johannsenite) of the same group, and "wollastonite" to white varieties, all possibly bustamite.

[7] Patches of calcitic ore in No. 3 Lens ore formation are apt to have No. 2 lens metal ratios.

zinc but are typical of No. 2 Lens ratios for lead and silver.

The zinc lodes.—Since completion of the Central Geological Survey work in 1939, developments in the Zinc Corporation and New Broken Hill Consolidated mines have provided much additional information concerning the zinc lodes. Haddon F. King in early 1947 arrived at a tentative structural interpretation which was essentially confirmed and extended by Gustafson and King a few months later. The King-Gustafson interpretation given here is considerably different from the tentative one proposed by the Central Geological Survey in 1939. No microscopic work has been done on the new exposures.

In the south end of the Zinc Corporation mine and in the New Broken Hill Consolidated mine two prominent ore horizons and a few lesser mineralized beds exist stratigraphically above No. 2 Lens formation. These horizons are eroded where they would be in the ore-bearing folds in the central part of the field. They are insignificant at the north end of the field. Consequently the south end is discussed.

RHODONITIC ZINC LODE: The lower zincy ore bed, known as the "Rhodonitic Zinc Lode", occurs about 125 feet, measured perdendicular to bedding, above No. 2 Lens. Where strongly mineralized on the limb of a fold but near its nose, the bed may be 40 feet thick. Where weakly mineralized, it may be unrecognizable or may consist of two narrow strands of feebly mineralized "garnet quartzite".

Better-grade ore consists of massive sulphides, chiefly sphalerite in marked preponderance over galena, some pyrrhotite with lesser amounts of pyrite and chalcopyrite along the margins, and a gangue of abundant "rhodonite", "hedenbergite", quartz, "garnet quartzite", rare green fluorite, and occasionally "garnet sandstone" and unreplaced pegmatite containing green microcline. Rarely a little calcite occurs in this lode. Such ore may run 7 per cent Pb, 1 oz. Ag, and 15 per cent Zn.

Some high-lead ore shoots with typical No. 2 Lens ratios occur in the lode. Low-grade portions may be massive "rhodonite" and "hedenbergite"[8] and/or "garnet quartzite" with sparse sulphides. All signs of "rhodonite" and "hedenbergite" may disappear along strike, and the only sign of the lode may be poorly metallized "garnet quartzite". Löllingite has been noted in drill core. In general, the favorable bed is much more erratically and incompletely metallized than No. 2 Lens formation or no. 3 Lens formation. Less than 50 per cent of the formation is ore-bearing in most mine cross sections.

SILICEOUS ZINC LODE: The upper important zincy ore bed known as the "Siliceous Zinc Lode", occurs about 30 to 60 feet measured perpendicular to bedding, above the "Rhodonitic Zinc Lode". It appears to be about 10 to 40 feet thick where not thickened or considerably thinned by folding. Ore-bearing portions appear to be somewhat more continuous than in the Rhodonitic Zinc Lode. High-grade ore, similar in assay value to high-grade ore in the Rhodonitic Zinc Lode, consists principally of sphalerite preponderate over galena small amounts of pyrrhotite, pyrite and chalcopyrite, fine-grained quartz, and fine-grained garnet with small residual remnants of unreplaced pegmatite and "garnet quartzite". Subordinate ore shoots have typical No. 2 Lens metal ratios. Calcite in small quantity is rarely seen in the ore. Lower-grade portions are merely poorly mineralized "garnet quartzite" and pegmatite. "Hedenbergite" has been seen only rarely and "rhodonite" has not been recognized.

OVERWALL ZINC LODE: Another zinc lode, a 5- to 10-foot lode known as the "Overwall Zinc Lode", occurs only about 40 feet above No. 2 Lens formation between it and the Rhodonitic Zinc Lode. This lode contains some "hedenbergite", and locally it contains conspicuous pink fluorite. It has some minable ore shoots. Metal ratios are typically those of the other zinc lodes but occasionally are like No. 2 Lens ratios.

OTHER ZINC LODES: Other smaller, less important, less well known, and probably discontinuous siliceous zinc lodes occur above the Siliceous Zinc Lode. Their oxidized outcrops contain conspicuous gahnite.

Favorable rocks and selective replacement.—The authors are not sure why some beds were favorable to replacement, others not. Certainly the

[8] Since this paper was written, specimens of "hedenbergite" from this formation were found by W. T. Schaller to have beta indices corresponding to hedenbergite, pyroxene (1.71±), and hornblende (1.65±).

favorable beds so nearly resemble the rest of the rock as to be virtually indistinguishable where neither ore-bearing nor highly altered. However for economic reasons they are seldom exposed by either underground workings or by drill holes beyond the limits of metallization or of intense hydrothermal alteration. Thus their study is difficult.

ORIGINAL CHEMICAL DIFFERENCES: The fact that the No. 3 Lens ore body is characterized by, rhodonite having distinctive Ca-Mn-Fe ratio conspicuous pink fluorite and a distinguishing Pb-Ag-Zn ratio, whereas the No. 2 Lens ore body is characterized by a calcite gangue with subordinate rhodonite having different Ca-Mn-Fe ratio and generally little or no fluorite as well as by a different Pb-Ag-Zn ratio, strongly suggests that the beds originally differed in chemical composition. It suggests, moreover, that differences in chemical composition may have been a deciding factor in selective replacement.

Gustafson (1939, p. 17) considered the possibility (a) that the high-manganese content of No. 3 Lens and high-lime content of No. 2 Lens were due to differences in sedimentation of the two formations, and (b) that these components were merely greatly rearranged (recrystallized and transported) by the ore solutions rather than introduced by them as previously concluded by Andrews (Andrews *et al.*, 1922) and Stillwell (1926). He concluded, nevertheless, that "if chemical composition was an important factor in determining the favorableness of certain beds, the part it played was neither simple nor obvious", and that the calcite, rhodonite, and garnet in the ore had probably been hydrothermally introduced.

Burrell (1942) now favors the hypothesis that the favorable formations were originally calcitic, siliceous, ferruginous, manganese carbonate (or oxide) beds intermixed with clays and sands; that the calcite, apatite and quartz of the lodes were in large measure sedimentary constituents; that the rhodonite and garnet were preponderately formed during regional metamorphism; and that these "early complex" minerals gave the beds a brittleness and a distinctive chemical character that accounts for their favorableness during the later introduction of lode pegmatite, fluorite, and sulphides and for the selective control exerted by them on sulphide deposition which resulted in the characteristic metal ratios of the ores. Among the arguments for this hypothesis are:

(1) Metamorphosed siliceous, calcareous, and manganiferous sediments in India and Brazil produced mineral assemblages not unlike the gangues of the Broken Hill lodes.

(2) Differences in characteristic lime-iron-manganese ratios of stratigraphically neighboring ore beds noted in manganiferous sediments throughout the world resemble the differences in lime-iron-manganese ratios of rhodonite in the Broken Hill lodes.

(3) The persistence and regularity of such differences is readily explained by selective sedimentation, and a similar process may have produced the original differences in the mineral assemblages of the various ore beds at Broken Hill.

(4) The influence of such original differences upon replacement activity might explain the development of characteristic metal ratios in each ore bed.

This theory does explain how rhodonite and calcite became selectively distributed, if not how millions of tons of sphalerite, galena, pegmatite, and fluorite were introduced into the ore beds so that each bed has its own diagnostic metal ratios and gangue characteristics. It is hard to escape the belief that some selective catalytic action by calcite, rhodonite, and garnet (if not by less obvious constituents of the replaced strata) affected the precipitation of sulphides and fluorite.

Probably the strongest arguments against the sedimentary-metamorphic hypothesis and for the hydrothermal hypothesis are:

(1) The ore beds wherever traced for even a few feet on strike or down dip beyond the limits of commercial mineralization do not contain conspicuous rhodonite or calcite, but are made up of thin beds of garnet "quartzite" and altered gneiss. Elimination of the beds through attenuation on the limbs of folds during folding does not appear to explain the absence of calcite or rhodonite in many instances. For example, there are no limy beds of No. 2 Lens formations above the No. 3 Lens ore in some parts of the small eastern folds in the South and Central mines where calcitic ore is missing. Yet here

beds are bunched in the nose of a fold, not attenuated. Another example can be found in the Rhodonitic Zinc Lode. Generally, where sulphide mineralization is strongest, there is abundant brown and pink rhodonite; where sulphide mineralization is weaker there is hedenbergite and "garnet sandstone" with subordinate rhodonite; where sulphide mineralization fades out, there is lavender garnet "quartzite" spotted or veined with occasional growths of hedenbergite and rarer rhodonite. Yet the widths of the formation may be constant. Consequently, if the "sedimentary hypothesis" is valid, one must assume that (a) No. 2 Lens, No. 3 Lens, and the favorable beds occupied by the Rhodonitic Zinc Lode all possessed the high manganese or high lime content in an extremely elongated channel of sedimentation which later became the crest of the Western anticline, and that (b) these beds became, except for the minor exceptions of large rhodonitic areas in No. 3 Lens and in the Rhodonitic Zinc Lode, practically 100 per cent replaced by ore wherever they were so composed.

(2) In addition to the intimate spatial relationship of rhodonite, garnet, "garnet sandstone", and calcite with sulphides and fluorite, the textures of these mineral aggregates and their cross-cutting relationship to bedding planes clearly indicate that they were in many cases transported by and crystallized from hydrothermal solutions during the ore-forming period. Every gradation can be observed underground between hydrothermally relatively unaltered banded sillimanite gneiss through banded silicified gneiss with alternating bands of "garnet quartzite" to pure lavender "garnet quartzite", and between "garnet quartzite" and "garnet sandstone". There are also good cases of coarse hedenbergite veining "garnet sandstone", and of "garnet sandstone" veining blue hydrothermal quartz.

All observers agree that most of the rhodonite, lode garnet, and calcite are earlier than the sulphides, but Burrell (1942), contrary to Andrews (andrews *et al.* 1922) and Stillwell (1926), thinks that these silicates also antedate the lode pegmatite. Gustafson and Garretty are unsure as to the conflicting evidence on this point but question its significance. Much of the coarse-grained silicates and calcite seen in stopes was either dissolved, transported and precipitated by ore solutions or introduced by ore solutions. These gangue minerals could be earlier than lode pegmatite and still be hydrothermal.

ORIGINAL PHYSICAL DIFFERENCES: The close dependence of mineralization on structure indicates that relatively high permeability distinguished the favorable beds from others. The shapes into which they were crumpled indicate a high degree of plasticity during folding little, if any, different from that of adjacent unfavorable beds. It is thus difficult to see how crushing during folding could have induced such selective permeability.

Nevertheless, meager evidence in the case of the zinc lodes at least suggests that favorable beds consisted of alternating thin layers of quartzite and shale (before metamorphism to gneiss), whereas some unfavorable beds at least were more homogeneous. Excessive slipping on well-defined bedding planes separating materials of different competency may have induced greater permeability.

Although all rocks may have behaved more or less alike under the extreme conditions of folding, they did not necessarily behave alike under the wholly different temperature-pressure conditions accompanying post-folding movements. Possibly during the adjustment of the folded pattern to later movements most of the "take up" occurred in the favorable beds as well as on the stretched limbs of folds. If so, any initial inequality of permeability must have been accentuated. (It will be demonstrated later that post-folding movements developed shears on stretched limbs.)

OTHER FACTORS: The cross sections show extreme thinning of ore on the limbs of the Western anticline. Most, but not all, of this thinning is due to stretching of the favorable beds during folding (with compensating thickening in the crests of folds). Intensity of mineralization and amount of ore decrease with distance from the anticlinal arch. Where in some cases, drives have followed the strike of a mineralized bed beyond the limits of sulphides, sulphides give way to highly garnetized and silicified rock which in turn grades into less altered rock, not because favorable beds are eliminated but because they are merely not mineralized. A few

rock laminae within the favorable bed continue to be mineralized much beyond the others—evidence of selectivity *within* the favorable formation where mineralization is less intense. Moreover, in one cross section of the Western anticline, No. 3 Lens may appear as a considerable thickness of lode material, in another cross section as a narrow band of sulphides in the arch of the fold. It may be safely assumed that more rock laminae belonging to the No. 3 Lens formation have been replaced in the first instance. The evidence is even more compelling in the case of the zinc lodes.

Thus favorable formations sometimes appear to be less definite things than favorable surfaces such as rock contacts, and the thickness of ore at any place in a "favorable formation" appears in some measure to represent the width of rock replaced on one or both sides of the favorable bedding plane along which ore solutions entered. The width may have been determined partly by the extent of crushing of adjacent rock layers, partly by the intensity of mineralizing agencies.

MERGING OF ORE BODIES IN FAVORABLE HORIZONS: Ore bodies in the two favorable rock horizons sometimes merge or are separated by a very thin partition of unreplaced rock.

There are several reasons:

(1) Thin barren rock partitions are stoped along with ore if they are too small to be left as pillars. Where the structural interpretation has been carried through old inaccessible stopes, no record of thin partitions remains. We frequently had to divide the ore of a stope into two horizons merely on the basis of projected structure without evidence of intervening rock even where it may have existed.

(2) Replacement in some places has progressed from formation to formation along small subsidiary shears.

(3) Intervening rock in some cases was probably either squeezed out during folding or, more probably, so crushed that ore solutions replaced it along with the normally more favorable rock.

STRATIGRAPHY

Stratigraphic Succession

The chief rock types have been mapped and described by Andrews and his associates (Andrews *et al.*, 1922). The Central Geological Survey attempted to subdivide the rock assemblage into stratigraphic units (Table 3), determine the order of sequence of these units, and solve the structures they portray. The newer interpretation differs from the older chiefly in that: (1) Rock formations are now correlated on the two sides of the main lode (notably the Footwall gneiss with the Potosi gneiss, the Alma augen gneiss with the Hanging Wall granite, and amphibolites of the Hanging Wall basin with certain ones to the east. Andrews' cross section reveals a somewhat similar tentative correlation although he does not stress it in the text. (2) Great thicknesses of sillimanite gneiss are split up into smaller rock formations. (3) The new structural picture differs radically from the older one in detail, although it harmonizes with the larger structures previously recognized.

Description of the Formations[9]

General outline.—The absence of persistent "key" "horizons" everywhere distinguishable form all other rock layers and inability to recognize top and bottom of beds were the greatest obstacles to the complete solving of either rock successions or folded structures. The gradation of fine garnets to coarse garnets in a sillimanite gneiss near a sharp quartzite contact is apparently evidence of approach toward the top of a clay bed overlain by a sand bed. It is very rare, however, to find exposures where the technique is applicable.

The old granite sills or the amphibolites are easily separated from other rocks, but many layers of each cannot be told apart. The Potosi gneiss and Footwall gneiss (here correlated) also can ordinarily be distinguished from the other rocks. Among the sedimentary rocks generally, however, each formation contains sillimanite gneiss beds of coarse and fine grain, quartzite beds, and often pegmatite layers. Beds containing coarse garnets are fairly reliable markers,

[9] The Andrews monograph (Andrews, *et al.* 1922) gives petrographic descriptions, photographs and chemical analyses of the various rock types. It should be noted that the two petrographers, (Browne and Stillwell) disagree as to the origin of the "quartzites", "Footwall gneiss", "Potosi gneiss", and amphibolite.

TABLE 3.—STRATIGRAPHIC SUCCESSION

Group	Formation No.	Formation Name	Thickness* (Feet)	Description
OVERALL GROUP	XVII	Hanging wall granite	2000	Pre-folding intrusive sill of porphyritic granite, now granite gneiss with augen on platy texture containing 1 narrow layer of gneissic aplite.
	XVI	XVI Formation	800	Sillimanite gneiss with considerable coarse-grained garnet; subordinate quartzite beds.
	XV	Town amphibolites	200	Pre-folding intrusive sills of gabbro, 1–4 in number, now amphibolite.
	XIV	XIV Formation	150	Sillimanite gneiss with thin beds of quartzite and fine-grained granular gneiss. One diagnostic, thin, well-bedded garnet-magnetite bed at bottom locally. Occasional small quartz-gahnite lodes.
	XIII	Bonanza amphibolites	10	Local thin amphibolite sill(s).
	XII	Potosi-Footwall gneiss	200–500	Granular gneiss, lacking sillimanite; contains round garnets and numerous highly folded pegmatite stringers; probably sedimentary.
LESSER ZINC LODE GROUP	XI	XI Formation	500	Where unaltered, sillimanite gneiss bands alternating with 2 bands containing chiefly quartzite beds; local garnet-magnetite bed near top. At Zinc Corporation, South Mine, and elsewhere, contains zinc sulphide and gahnite-bearing lodes and much "garnet quartzite".
	X	Consols amphibolites	200	1–2 (or more ?) local amphibolite sills.
	IX	IX Formation†	200	Where unaltered, sillimanite gneiss containing at least 2 wide coarse garnet bands. A few local zinc and quartz-gahnite lodes.
MAIN ZINC LODE GROUP	VIIIb	Siliceous zinc lode formation†	25	Lode or "garnet quartzite". Not identified where unreplaced.
	VIIIa	VIIIa Formation†	45	Alternating layers thinly bedded gneiss and quartzite (or "quartzite").
	VIII	Rhodonitic zinc lode formation†	25	Lode or "garnet quartzite". Not identified where unreplaced.
	VII	VII Formation†		Alternating layers thinly bedded gneiss and quartzite (or "quartzite") containing at least 1 zinc lode of importance ("Overwall zinc lode").

TABLE 3.—*Continued*

Group	Formation No.	Formation Name	Thickness* (Feet)	Description
MAIN LEAD LODE GROUP	VI	No. 2 Lens ore formation	50	Lode or "garnet quartzite". Not identified where unreplaced.
	V	V Formation	70	Coarse-grained sillimanite gneiss.
	IV	No. 3 Lens ore formation	50	Lode, "garnet sandstone" or "garnet quartzite". Not identified where unreplaced.
UNDERWALL GROUP	III	III Formation	500	Coarse-grained sillimanite gneiss with subordinate beds of fine-grained granular gneiss, both generally with abundant coarse garnets; subordinate thin beds of quartzite.
	II	Underwall amphibolites	50	1 or 2 amphibolite sills; probably local.
	I	I Formation	400 (exposed)	Like III formation
		Total 4900 (+) − 5500 (+)		

*Thickness given is a rough guess as to average thickness, allowing for packing and duplication in the noses of folds and for attenuation on the limbs of folds. The figures give only relative orders of magnitude.

†Where the zinc lodes are not mineralized we are unable satisfactorily to distinguish Formations VII–IX inclusive.

for short distances at any rate, but there are too many of these and they all look alike. Formations must therefore, with few exceptions, be distinguished by their varying proportions of component rock types common to all, and by their stratigraphic position in known structures. Where the walls of crosscuts are dirty or the rocks are highly altered close to lodes, recognition of formations is commonly impossible. Rocks also have been rendered indistinguishable in places by shearing and schisting.

Table 3 and the illustrations of this paper are the final interpretation of countless factual data insofar shown on plans and work sheets supplied to each mine and on file in Broken Hill (Gustafson 1939) but too bulky to present in this paper.

Most of the descriptive terms used are self-evident. Quartzite means true sedementary quartzite as distinct from "quartzite" a product of hydrothermal silicification.[10] Coarse-grained garnet means garnet at least one-half an inch in diameter. The various amphibolites are all very similar and are the metamorphosed gabbro sills (Table 1, item 2). There may be errors in the correlation of these, because individuals may transgress other formations, lens out, or bifurcate. However, they are remarkably persistent in lateral extent and in stratigraphic position. They are all obviously highly folded. The granite gneiss is the older folded granite (Table 1, item 2). Numerous post-folding pegmatite dike occupying fractures in the older rocks and late uralite dolerite dikes are omitted from this discussion and from the plans and sections.

[10] The field evidence tends to confirm Stillwell's conclusions that the "quartzites" are sedimentary, and not intrusive, as Browne concluded (Andrews, *et al.*, 1922, Appendices I and II).

I Formation.—The oldest rock formation considered is exposed in deep drill holes in the Broken Hill Proprietary Company property and Block 14 and possibly on the surface in the Eastern anticline. It consists predominantly of fairly coarse-grained sillimanite gneiss containing fairly abundant coarse-grained garnets, and contains numerous but very subordinate thin quartzite beds (1 inch to 1 foot thick). The formation is indistinguishable from III Formation. The two form a sedimentary unit split by sills of the Underwall amphibolites. Minimum of 400 feet exposed.

A deep drill hole put down in 1890 by the Broken Hill Block Silver Mining Company (Brisbane Blocks drill hole No. 3) intersected "garnet sandstone" beneath amphibolite on the west limb of the Western anticline. This possible "No. 4 Lens" ore horizon in I Formation was the objective of a drilling in the B.H.P. Company mine which failed to find ore.

Underwall amphibolites (II Formation).—Amphibolite sills of this formation are exposed for certain only in deep drill holes in the Central Mine, B.H.P. Company mine, and Block 14. It is not certain that all the scattered drill-hole intersections in both the Western anticline and Eastern anticline belong to one continuous sill, but they are so interpreted on the large-scale cross sections. The thickness as revealed by drill core is variable. If but one sill is duplicated by folding, the thickness is perhaps 50 feet.

III Formation.—The rock resembles I Formation. It immediately underlies the No. 3 lens ore bodies and on the structural interpretation presented here is believed to outcrop as the core of the Eastern anticline east of the line of lode from Block 12 northward (Pl. 3, fig. 1). Thickness: probably 500 feet. The coarse garnets were generally destroyed by hydrothermal alteration within 50 feet of the lodes, though in some places they are found against the lode. In the Zinc Corporation the rock near the lodes locally appears slaty and well bedded. In Block 14, the South Mine, and elsewhere, a thin lode a short distance under the main ore body may be a locally mineralized bed in this formation.

No. 3 Lens ore formation (IV Formation).—Already described under "Folded Ore Horizons". Thickness: extremely variable, averaging perhaps 50 feet. This formation is more persistent as a recognizable unit beyond the limits of ore than are the other lode horizons. On the west limb of the Eastern anticline, this (?) horizon can be traced north of the east side of Imperial Ridge and Round Hill to where it meets the Globe-Vauxhall crush. Here it occurs in the main as a hard, silicified, fine-grained, manganese-stained rock approaching a "garnet quartzite" in appearance. It is finely bedded, and its bedding planes are generally highly drag-folded. This type of rock grades into true "garnet quartzite" which locally is mineralized.

Where No. 2 Lens ore formation and No. 3 Lens ore formation are both ore-bearing and outcrop close to one another along the main line of lode, No. 3 Lens generally contains more "garnet sandstone", whereas No. 2 Lens is harder, more siliceous, and contains more "garnet quartzite". Both are manganese-stained.

Ordinarily both ore horizons are difficult to trace, even underground, beyond the limits of ore. Neither is recognized on the surface with certainty on the east limb of the Eastern anticline or on either limb of the Alma anticline.

V Formation.—Where not too highly altered, this rock is a coarse-grained "mottled"[11] gneiss

[11] Mottling produced by fairly distinctive elongate white feldspar-quartz patches. All coarse-grained gneisses are more or less "mottled".

PLATE 2.—AERIAL VIEW OF BROKEN HILL AND TYPICAL LODE OUTCROPS

FIGURE 1.—AERIAL VIEW OF BROKEN HILL LOOKING NORTH

Zinc Corporation Mine in foreground

FIGURE 2.—NARROW GOSSAN MAIN LODE OUTCROP OF "SHEAR ORE"

Broken Hill Proprietary Company Ltd. mine

PLATE 3.—BROKEN HILL ROCK TYPES

FIGURE 1.—COARSE SILLIMANITE-GARNET GNEISS OF I OR III FORMATION IN NOSE OF EASTERN ANTICLINE NORTHEAST OF NORTH MINE

Photograph shows 45° southerly pitch.

FIGURE 2.—BANDED IRON FORMATION (GARNET-MAGNETITE ROCK OF XI FORMATION IN ALMA ANTICLINE SOUTH OF NORTH MINE

FIGURE 1

FIGURE 2

AERIAL VIEW OF BROKEN HILL AND TYPICAL LODE OUTCROP

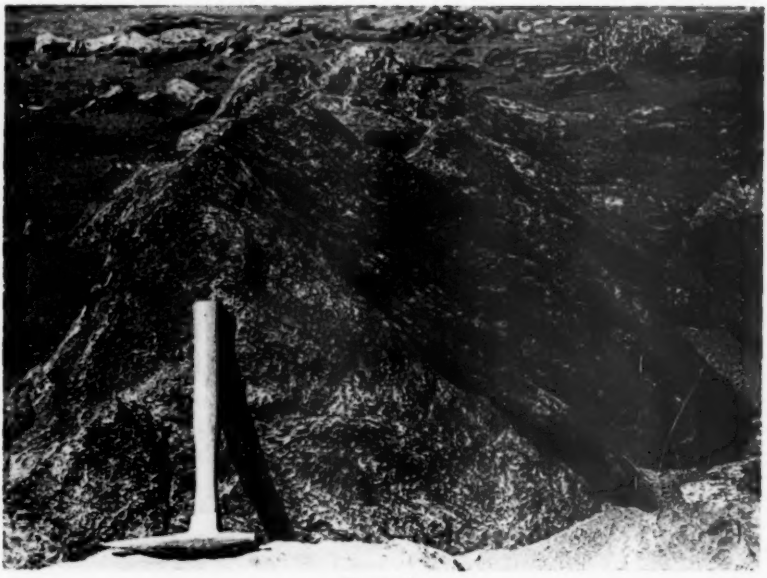

FIGURE 1

FIGURE 2

BROKEN HILL ROCK TYPES

FIGURE 1

FIGURE 2

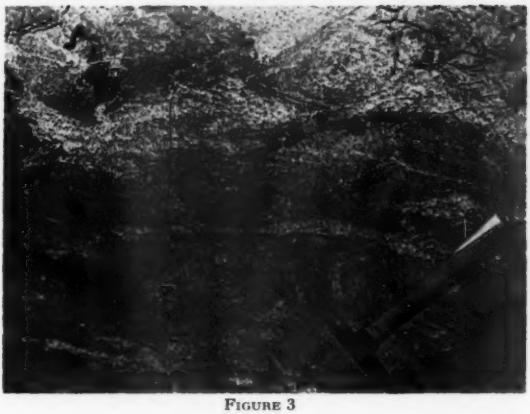

FIGURE 3

POTOSI - FOOTWALL GNEISS IN FOOTWALL BASIN SOUTH OF NORTH MINE
Note contorted pegmatite and round garnet porphyroblasts.

FIGURE 1

FIGURE 2

BROKEN HILL ROCK TYPES

with very subordinate thin quartzite beds. Bedding is seldom very conspicuous. Fine-grained garnets are occasionally in evidence, but garnets are almost never large or conspicuous, although the formation is beginning to carry coarse garnets on the deep levels of the Zinc Corporation and New Broken Hill Consolidated mines. Thickness: extremely variable, averaging about 50 feet.

No. 2 Lens ore formation (*VI Formation*).—Already described under "Folded Ore Horizons". Thickness: extremely variable, averaging perhaps 50 feet. The northern continuation of No. 2 Lens in the west limb of the Eastern anticline is less certain. Here the first quartz-gahnite lode above No. 3 Lens has been tentatively considered to be No. 2 Lens ore formation.

VII Formation.—Where observed the rock is generally composed of alternating layers of thinly bedded gneiss and "garnet quartzite" in varying ratios of abundance depending on the amount of alteration. In Zinc Corporation and New Broken Hill Consolidated property, it contains the narrow "Overwall zinc lode" already described. Thickness: about 125 feet.

Rhodonitic zinc lode (*VIII Formation*).—Already described under "Folded Ore Horizons." Thickness: averages about 10 to 40 feet. This formation occurs as an ore horizon only in the Zinc Corporation and New Broken Hill Consolidated mines. North of here it probably exists as a feebly mineralized "garnet quartzite", but it has not been identified with certainty. Where this and the upper zinc lodes are "missing", IX Formation is shown on plans and sections as immediately overlying No. 2 Lens ore formation.

VIIIa Formation.—Recognized as a separate formation only where the underlying and overlying zinc lodes (VIII Formation and VIIIb Formation) are mineralized, it generally consists of "quartzite" whose texture, where not too highly silicified, suggests derivation from thinly bedded sillimanite gneiss and quartzite. Thickness: 30 to 60 feet.

Siliceous zinc lode (*VIIIb Formation*).—Already described under "Folded Ore Horizons". Thickness about 10 to 40 feet. Ore-bearing only in the Zinc Corporation and New Broken Hill Consolidated mines. Not identified with certainty farther north.

IX Formation.—Well exposed on the surface of Block 14 west of the lodes, here it consists of two wide bands of sillimanite gneiss alternating with two somewhat narrower bands of sillimanite gneiss with conspicuous coarse-grained garnets. It can be recognized with fair certainty in a similar position in Block 10. According to our structural interpretation, the rocks immediately east of the Main Shear in the South Mine and (on upper levels) in the Central Mine belong to this formation. Here there is a lower narrow band of gneiss (5–50 feet thick) containing abundant coarse-grained garnets overlain by alternating thin beds of quartzite and gneiss which in turn are overlain by a considerable thickness of alternating thin beds of coarse-grained gneiss and fine-grained granular gneiss, both with medium- to coarse-grained garnets.

The formation is difficult or impossible to separate from XI Formation in many places. The rocks are considerably altered in the Zinc Corporation in the nose of the Western anticline. Thickness: believed to be about 100 to 200 feet. Where the zinc lodes are absent rock properly belonging to VIII, VIIIa, VIIIb, and X Formations has possibly been included in this formation.

Consols amphibolites (*X Formation*).—The Consols amphibolites comprise one or two (?) amphibolite sills. They are well exposed on the east side of the Footwall basin and wrap around the northern rim of this structure. Owing to their lenticularity, the correlation of individual sills on two sides of a fold may be in doubt as, for example, on the two sides of the Footwall basin, even though the amphibolites on the two sides clearly belong to the same formation. The amphibolites lens out on the west side of this Footwall basin going south before the South Mine property is reached.

PLATE 5.—BROKEN HILL ROCK TYPES

FIGURE 1.—TOWN AMPHIBOLITES IN ALMA ANTICLINE SOUTH OF ZINC CORPORATION MINE

FIGURE 2.—HANGING WALL GRANITE (AUGEN GNEISS) IN HANGING WALL BASIN NEAR NORTH MINE
Note coarse ragged garnets

They are everywhere missing west of the line of the line of lode south of the De Bavay fault.

Owing to the difficulty in distinguishing IX Formation from XI Formation, it is by no means certain that these amphibolites occur at the exact stratigraphic position recognized as the contact between these two formations in places where the amphibolites are missing. They probably merely approximate this position. The variable distance between Consols amphibolites and the Potosi-Footwall gneiss in the Footwall basin suggests that the amphibolite cuts across bedding planes at an acute angle. In fact there is independent clear evidence that the amphibolite sills cut across the other formations at an acute angle. The northernmost outcrops of the amphibolites in the Footwall basin may occupy as low a stratigraphic position as IV–VI formations. On the other hand, in M.Ls. 55 and 79 the same (?) sills are very close to XII Formation.

The interpretation of the structure north of the Imperial Dam fault is admittedly weak. Some of the lower amphibolites here may be Consols amphibolites rather than Town amphibolites. (*See also* later discussion of structure between the De Bavay Fault and Round Hill.) Thickness: probably averages 200 feet.

XI Formation.—The lowermost bed in this formation is regarded as the lowermost strong "quartzite" (or quartzite ?) lying above the upper band of coarse garnets in IX Formation. The upper limit of the formation is regarded as the Potsi-Footwall gneiss.

On the west flank of the Western anticline in Block 14 and Block 10 the formation consists of two strong bands containing chiefly quartzite ("quartzite ?") separated and overlain by sillimanite gneiss with very subordinate thin quartzite beds. In the Central Mine, South Mine, and Zinc Corporation it contains numerous siliceous zincy lodes containing gahnite. Lodes of this kind also occur in this formation in the North Mine, in M.L. 3, and elsewhere, although there are fewer of them. Most gahnite lodes outcropping from White Leads to Rising Sun North also probably belong to XI Formation. In contact with the Potosi gneiss in the Zinc Corporation and South Mine, also north of the De Bavay fault in M.L. 3, and at White Lands and Rising Sun is an altered gneiss containing abundant round fine-grained to medium-grained garnets. This rock is somewhat doubtfully assigned to XI Formation; it may be sheared altered Potosi (Footwall) gneiss. Below this rock in turn in M.L. 3 is a gneiss containing coarse garnets. Two bands of coarse garnets which probably belong to this formation were mapped in a similar stratigraphic position under the Potosi-Footwall gneiss in the Footwall basin just east of the De Bavay fault.

The quartz-gahnite lodes beneath the Footwall gneiss on both sides of the Footwall basin are assigned to XI Formation, but XI Formation and IX Formation are difficult to separate east of the line of lode. The rocks between the Consols amphibolites and the Footwall gneiss generally contain fewer quartzite beds than does XI Formation in the Western anticline and fewer coarse garnets than is typical of IX Formation in that structure. Just east of Kintore Shaft on the Central Mine, coarse garnets occur next to the Potosi gneiss. Either they belong to XI Formation, or XI Formation has been eliminated by shearing during folding.

Near the top of XI Formation not more than 20 feet or so below the Footwall gneiss there occurs locally a narrow layer (zero to 10 feet thick) of very distinctive rock termed a "garnet-magnetite lode" by Andrews (Pl. 3, fig. 2) and marked on our 100-scale surface plans furnished to the mines as BIF (banded iron formation). The rock is fine-grained, remarkably well and thinly bedded, and consists principally of garnet and magnetite, with subordinate quartz and apatite. The bedding planes are commonly wrinkled into small minor folds. In our opinion this bed and the very similar bed overlying the Footwall gneiss are sedimentary layers which, when present, are everywhere in the same stratigraphic positions[12].

[12] This "lode" is shown on Andrews' maps locally as cutting the Footwall gneiss and elsewhere as cutting sillimanite gneiss remote from the Footwall gneiss. Our mapping revealed very few instances where the bed is bordered on both sides by Footwall gneiss (probably infolded) and no instance where the bed is remote from the Footwall gneiss or Potosi gneiss. Where Andrews, (Andrews, *et al.*, 1922) shows the bed in sillimanite gneiss, we recognize on one side of it a band of Footwall gneiss not mapped by Andrews (the eastern limb of the Alma anticline). Whether or not the garnet and magnetite were introduced hydrothermally or are the metamorphic products

The bed outcrops abundantly on both limbs of the Alma anticline and in the nose of the Broken Hill basin, occurs in a number of the structures on the east side of Rising Sun and White Leads, and it, or the almost identical bed overlying the Footwall gneiss, has been observed but not mapped on the east limb of the Broken Hill basin. The bed, however, has not been found on either limb of the Eastern anticline or Western anticline except south of the Zinc Corporation. Thickness of XI Formation: about 500 feet.

Potosi-Footwall gneiss (XII Formation).—Andrews and his associates called the fine-grained phase of this formation the Potosi gneiss ("granulite") and the coarse-grained phase the Footwall gneiss. Andrews (Andrews, *et al.*, 1922, p. 86) and Browne (1922) regarded both as intrusives; Stillwell (1922) offered the minority opinion that they are sedimentary[13]. They look more like sediments than intrusives. What appear to be highly folded bedding planes can be seen locally. The most conspicuous banding in the rock is, however, due to its gneissic texture or to the parallelism of pegmatite veins (Pl. 4).

The Footwall gneiss, as defined by Andrews, is a moderately coarse-grained gray gneiss forming bold outcrops on the east side of the line of lode. It is distinctly granular and is composed chiefly of feldspar (orthoclase and plagioclase), quartz, biotite, and garnet. Sillimanite is conspicuously absent. The rock generally contains numerous fairly round garnets an eighth of an inch to half an inch in diameter. Generally it contains numerous small highly convoluted pegmatite stringers. The Potosi gneiss, very similar but finer-grained, generally occurs on the western side of the line of lode but was recognized by Andrews on the east side in the Central Mine. Portions of the Footwall gneiss as mapped by Andrews are fine-grained and could (we believe) be classed as Potosi gneiss with equal justice. In our structural interpretation, the two types are regarded as different phases of a single formation, probably sedimentary but in any case occupying a single stratigraphic position.

The formation occurs on the east side of the mines in the Footwall basin and in the west limb of the Broken Hill Basin (east limb of Alma anticline)[14]. Underground we have found it only in the Zinc Corporation and North Mine. West of the mines the formation occurs locally on both limbs of the Hanging Wall basin.

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of an iron-rich sediment is somewhat in doubt. In a few places at least the bed contains a few per cent of lead. In a few others, we were tempted to correlate with it a "garnet quartzite". The garnet, moreover, is a manganese-rich garnet like the lode garnet. On the other hand, wherever the bed outcrops, over a distance of many miles, it is always the same in appearance with no visible change in composition. If a lode (*i.e.*, a replaced bed), it is unique in its uniformity. Even detached pods of this bed in the De Bavay fault are no different from other exposures, a fact which suggests that the garnet and magnetite formed before the period of main faulting and therefore before the period of mineralization. The evidence favors the view that the bed is a metamorphosed iron-rich sediment into which, as into most of the other rocks in the district, a little galena found its way very locally during the main period of mineralization. It was noticed during the magnetic survey of the Zinc Corporation's southern leases that abnormal quantities of magnetite had been developed locally in the gneiss at amphibolite contacts. Elsewhere (especially at Imperial Ridge) the gneiss next to amphibolite has been profoundly altered by what may be contact metamorphism. Possibly the magnetite and garnet of the garnet-magnetite and quartz-magnetite "lodes" of the district were introduced hydrothermally into favorable beds by "ore solutions" emanating from the reservoir of gabbro magma from which the amphibolite sills were also ejected. If so these "lodes" have suffered dynamic metamorphism and folding.

[13] Chief arguments given for an intrusive origin are:

(1) The rock masses are lenticular. They do not, however, appear to be necessarily more lenticular than other sedimentary gneiss types. Excessive thinning on the limbs of folds and packing in the noses will probably explain their lens-like character even if sedimentary lenticularity is not used as an argument. The biggest "lenses" are structural basins.

(2) There is said to be contact alteration next to them. The alleged "contact alteration" is apparently the local development of staurolite and probably andalusite in adjoining gneisses. But these minerals are widespread through the district znd can be accounted for as products of the regional metamorphism. In our mapping we found no evidence of peculiar alteration at the contacts not found in the gneisses elsewhere.

(3) Their chemical composition suggests igneous rocks. Yet Stillwell thought the chemical analyses favor a sedimentary origin! At best the chemical evidence is inconclusive.

(4) They contain numerous small highly folded stringers of pegmatite, but so do locally the sillimanite gneisses. It is perhaps noteworthy that the old amphibolite sills generally do not. Perhaps bedding planes afforded easiest access to the old pegmatites.

[14] Shown as sillimanite gneiss on Andrews maps except for one isolated outcrop east of Round Hill which is marked Potosi gneiss.

It also appears in the Zinc Corporation and South mine in what appears to be a small syncline in the west limb of the Western anticline. It is missing over a portion of the field in the east limb of this structure and where present it is very narrow, probably as a result of attenuation during folding. (The formation is obviously highly folded and greatly thickened in the trough of the Footwall basin.) Thickness: extremely difficult to determine; probably averages between 200 and 500 feet.

Bonanza amphibolites (XIII Formation).—Immediately overlying the Footwall gneiss in the Footwall basin near the Bonanza Shaft in M.L. 222 is a small lenticular amphibolite. The formation is not recognized with certainty elsewhere. Doubtfully correlated with it west of the mines is the easternmost amphibolite in Block 10, Block 14, and British mines, although this may belong to the Town amphibolites (XV Formation). The formation is apparently missing on the east limb of the Alma anticline. It might be better to regard all the amphibolites above the Potosi-Footwall gneiss as belonging to one formation and all the sillimanite gneiss between the Potosi-Footwall gneiss and the Hanging Wall Granite as belonging to another.

XIV Formation.—The rocks overlying the Potosi-Footwall gneiss are for the most part a fairly featureless assortment of sillimanite gneiss beds alternating with thin layers of quartzite and fine-grained granular gneiss. Garnets are nowhere conspicuous. Locally a poor quartz-gahnite lode occurs near the bottom of the formation. In places on both limbs of the Alma anticline immediately overlying the Potosi-Footwall gneiss or separated from it by a few feet of coarse sillimanite gneiss is a thin garnet-magnetite bed normally indistinguishable from the one in XI Formation. This upper one appears to be somewhat more persistent, and we suspect that it contains more magnetite. In places on the east limb of the Alma anticline the magnetic bed has apparently been duplicated by minor folding (or there is locally more than one bed).

The Silver Hill, Potosi, Silver Peak, Globe, Star, and Carbonate Ridge mines, all of which have produced a little ore, appear to be in XIV Formation on the west limb of the Hanging Wall basin, but were not studied. Thickness of the formation: probably 150 feet.

Town amphibolites (XV Formation).—This formation comprises a group of amphibolite sills that outcrop abundantly on the edge of town of Broken Hill on both sides of the Hanging Wall basin (Pl. 5, fig. 1). In many places only one amphibolite is present; in others there appear to be as many as four, although the amount of duplication by minor folding is unknown. Also assigned to this formation are amphibolites in the same approximate stratigraphic position on the east limb of the Alma anticline. Thickness: estimated at 200 feet.

XVI Formation.—This formation, between the Town amphibolites and the Hanging Wall granite, is composed chiefly of sillimanite gneiss of both coarse and fine grain with subordinate thin quartzite beds. A fair percentage of the coarse gneiss contains abundant and conspicuous coarse garnets. Thickness: seen only on (thinned) limbs of folds; probably 800 feet.

Hanging wall granite (XVII Formation).—This uppermost formation dealt with is essentially a sill of gneissic porphyritic granite (Table 1, Item 2) although locally some of the rock comprising it appears to be metamorphosed granitized sedimentary rock. It outcrops prominently in the Hanging Wall basin at Lord's Hill, Billy Goat Hill, and the Abbatoir Ridge (Hanging Wall gneiss of Andrews). It also forms bold outcrops on the east limb of the Alma anticline in the town of Alma in Hebbard Street, along Turpin's Ridge, and for some miles north and south (Alma augen gneiss belt of Andrews). Where more foliated than elsewhere, it has been referred to by Andrews as "platy gneiss". The most prominent minerals are quartz, orthoclase (and subordinate plagioclase), biotite, and garnet (Pl. 5, fig. 2).

A band of aplite up to 200 feet wide is commonly in the granite mass. This appears to have been a separate intrusive slightly later than the main granite mass. In some places it is near the center of the granite sill (Turpin's Ridge); in others at or near the top (Alma Township); in still others near the bottom (Lord's Hill). In the De Bavay quarry at Lord's Hill, sillimanite gneiss locally intervenes between granite and aplite.

Although not indicated as a separate formation, underlies a much thinner granite sill locally the main body and is separated from it by from 500 to 200 feet, as for example at the north end of the Billy Goat Hill exposures and along the west side of Turpin's Ridge. Thickness: probably at least 1000 feet.

Structure

Introduction

Geological problems of economic importance in Broken Hill are primarily structural. The Central Geological Survey's energies therefore were chiefly spent in a detailed and comprehensive analysis of the structure. Because the structures are very complex, and because some of our major conclusions are based on what may at first appear to be small structural details, a complete understanding of the problem demands thorough and critical study of many plans and sections, only a few of which can be presented in a paper such as this. The following discussion summarizes our views and appraises the validity of our conclusions where based on incomplete or unsure evidence.

Two principal types of structures are discussed: (1) folds, the products of tremendous southeast-northwest shortening in the earth's crust which plastically deformed every cubic inch of rock in the district, and (2) faults and "buckles", the products of later stresses of smaller magnitude that were relieved very locally at places of weakness. Faults and buckles offset and deformed the already existing folds.

The folded structure between Barrier South shaft and the De Bavay fault is much better understood than it is either south or north of these limits. Therefore, discussion, insofar as it is concerned with folds between the Hanging Wall basin and the Footwall basin, is confined to the central portion of the field. Understanding of the structural interpretation here makes possible extension of the interpretation north and south.

In projecting complex structures to unexplored depths of a mile below the surface and to eroded heights of a mile above the surface, as has been done on the cross sections, very considerable inaccuracies are inevitable. Nevertheless, these cross sections are not merely uncontrolled "sketches" of what might be. All observations of pitch and dip made on the surface and underground were utilized in their construction. Axial lines for the underwall and overwall of most of the recognizable rock formations in each recognizable fold—more than 50 axial lines in all—drawn in longitudinal projection in such a way as to satisfy all of our scattered information, were used to guide the drawing of the cross sections. Thus each cross section is consistent with all of our pitch-dip-position data for the whole line of lode.

Major folds

Introduction.—From east to west the major folds[15] in this district are: (1) the Broken Hill basin, (2) the Alma anticline, (3) the Footwall basin, (4) the Eastern anticline, (5) the Eastern syncline, (6) the Western anticline, (7) the Hanging wall basin, and (8) the Broken Hill arch (Pl. 1). The main ore-bearing structures are minor folds which embroider the Eastern anticline (west limb), the Eastern syncline, and Western anticline. All folds, with the possible exception of the Broken Hill arch, are tight, isoclinal, complex folds with nearly vertical limbs.

Broken Hill basin.—This large structure, clearly shown on Andrews' maps, is 20 miles long and 4 miles wide. Only a portion of the western rim was mapped by the Central Geological Survey, although a large part of it was examined.

Broken Hill arch.—West of Beryl Street in Broken Hill, large quartzite beds make their appearance, whereas the amphibolites and granite gneisses found to the east are missing. The latter have been eroded from the broad Broken Hill arch which embraces the town and extends for some miles westward (Andrews et al., 1922). This structure was not mapped by the Central Geological Survey, nor are its rocks described in this paper.

Hanging Wall basin.—East of the Broken Hill arch is a narrow basin whose axial plane lies parallel to and between Argent and Crystal Streets. Its maximum width is about 4000 feet.

[15] (1) Items (1), (7), and (8) were named by Andrews and his associates (Andrews, *et al.*, 1922) who also recognized the existence of (5) and (6).

Owing to lack of outcrops, little is known about this structure south of the municipal boundary. Its undulatory pitch is revealed by outcrops of the Hanging wall granite. A major crest in the pitch line occurs opposite the B.H.P. Mine, and a major trough in the pitch line occurs in the vicinity of the De Bavay fault.

The syncline is cut by the strong Globe-Vauxhall crush zone which runs roughly parallel to its axial plane and along its western rim just inside the Potosi-Footwall gneiss formation. Movement on the fault appears to have been west side northward, the western rim of the basin (as defined by the Potosi-Footwall gneiss) having been carried about 2½ miles north of the eastern rim (as defined by the No. 3 Lens ore formation)[16] at the northern extremity of the basin where the two rims (as defined by the same formation) would ordinarily meet. The Consolidated Mine is situated where the No. 3 Lens ore formation at the eastern rim meets the fault, about 4 miles north of Broken Hill. Only a portion of the eastern rim of the Hanging wall basin was mapped by the Central Geological Survey.

Footwall basin.—Not mentioned by Andrews, but comparable in size to the Hanging wall basin, is the Footwall basin, clearly marked by the Potosi-Footwall gneiss outcrops east of the line of lode. The nature of its southern continuation south of the Zinc Corporation mine is in doubt because of lack of outcrops. Its pitch line is roughly parallel to that of the Hanging wall basin with a crest opposite the B.H.P. Mine and a trough in the region of the De Bavay fault. Small minor folds with flattish west dips in Dunstan's Quarry (M.L. 285) indicate strong (but local?) overturning to the east. Most of this basin was mapped in the critical area.

Alma anticline.—An anticline between the Footwall basin and the Broken Hill basin is a structural necessity. Our mapping suggests that this anticline is an extremely tight sheared one in which rock formations are greatly attenuated, some being eliminated completely for considerable distances. The structure is about 800 feet wide. The Consols Amphibolites give eloquent testimony to the tight folding, although many details are obscure. Single limbs are not everywhere distinguishable from double limbs. The behavior of pitch lines could not be satisfactorily determined. The gneisses and quartzites in Eyre and Piper streets in Alma (South Broken Hill) west of Foulke's Ridge have not been assigned formation names with any confidence. No. 3 Lens ore formation should probably either outcrop here, or approach fairly close to the surface, but has not been recognized. Some small "garnet quartzite" outcrops are the only signs of mineralization. A large portion of the Alma anticline was mapped in the critical area.

Western anticline, Eastern syncline, and Eastern anticline.—The dominantly anticlinal region between the Hanging wall basin and the Footwall basin, about 1200 feet wide, is extremely complex. Its major structural elements the Western anticline, Eastern syncline, and Eastern anticline, are each made up of many smaller folds[17] which are important because they contain the main Broken Hill ore bodies. It is not, however, the number of minor folds so much as the differences in their shape and attitude from place to place that makes their study so difficult.

Figures 7 to 12 inclusive, a series of cross sections at intervals from south to north, illustrate the relationship of the three major structural elements under discussion. Figure 7, a cross section through the Central Mine, shows the Western anticline to be considerably elevated with respect to the Eastern anticline and the Eastern syncline to be greatly depressed with respect to either anticline.

Figure 8, a cross-section through the B.H.P. Mine, reveals a gradual change in the relative positions and shapes of these structures. The Eastern anticline has moved up with respect to the Western anticline, and some of the more easterly minor folds comprising the Eastern

[16] The Potosi-Footwall formation has not been recognized where it would form the eastern rim in this vicinity. Assuming a position for it on the basis of stratigraphy, the *apparent* horizontal component of fault movement at this place is about 3 miles, although the actual movement may be considerably less. The vertical component of movement is unknown, but is b elieved to be very small in comparison with the horizontal component.

[17] In turn made up of still smaller folds, and so on down to wrinkles of microscopic proportions. The other major folds already discussed are similar in this respect but have not been analysed in such detail.

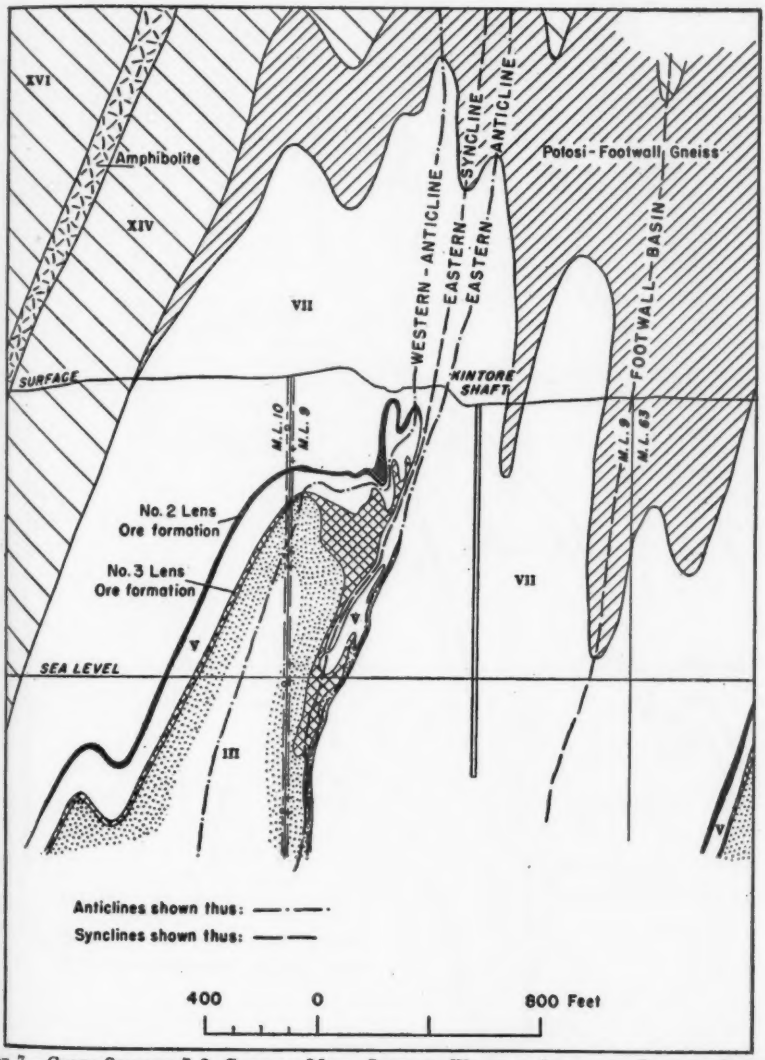


FIGURE 7.—CROSS SECTION 7–8, CENTRAL MINE, SHOWING WESTERN ANTICLINE, EASTERN SYNCLINE, AND EASTERN ANTICLINE

anticline (presumably too deep to show in Figure 7) have rolled up into the nose of that structure and made it broader. The Eastern syncline is still in part a deep elongated fold.

In Figure 9, a cross-section through the Block 14 Mine, the long attenuated portion of the Eastern syncline has disappeared; the Eastern anticline, as defined by the ore formations, is now considerably higher than the Western anticline and has been eroded.

Figure 10, a cross-section through the southern part of the British Mine shows the Eastern syncline moved up with respect to both the Western anticline and the first prominent synclinal component of the Eastern anticline. Eastern portions of the Eastern anticline, however,

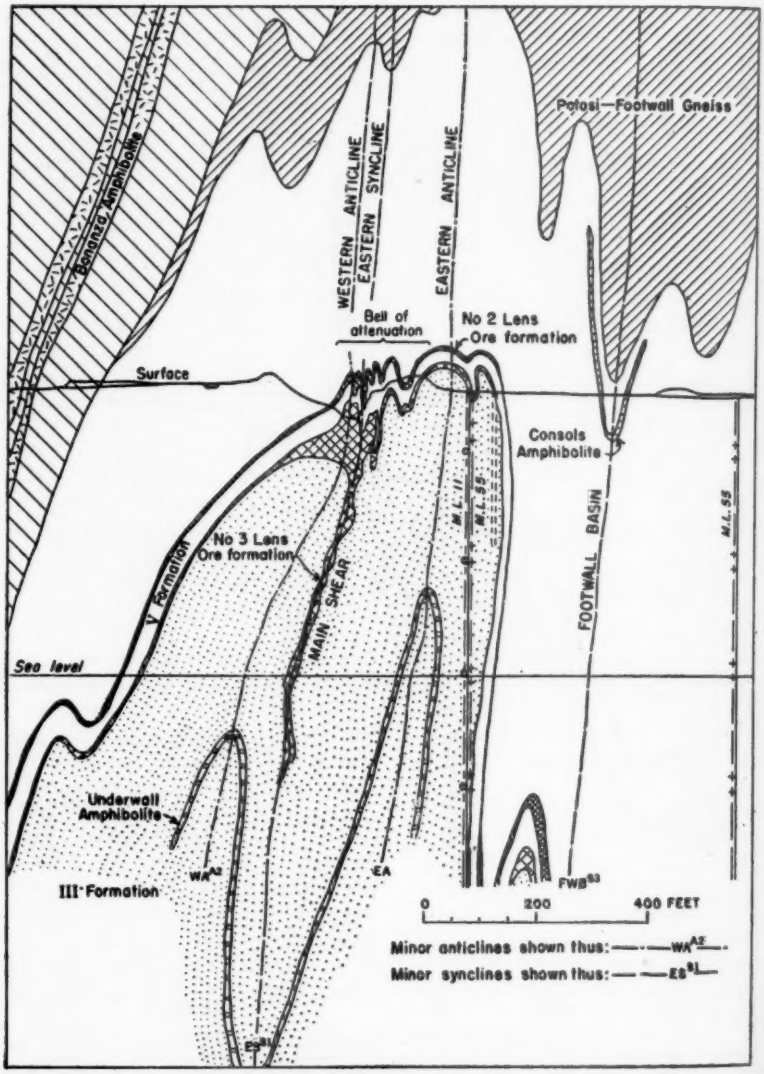


FIGURE 8.—CROSS SECTION, B. H. P. MINE (3520), SHOWING WESTERN ANTICLINE, EASTERN SYNCLINE, AND EASTERN ANTICLINE

have continued to roll up and are now well above the Western anticline.

Figure 11, a cross-section through the northern part of the British Mine, reveals much the same situation with the main arch of the Eastern anticline cut off by the British fault. The Western anticline has virtually disappeared as an ore-bearing structure.

Figure 12 is a cross-section through the Junction and North Mine. Precise correlations of small structures across the British fault are impossible. The Junction, Junction North, and North Mine ore-bearing folds are, however, believed to be the same minor folds that carry ore in the Thompson section of the British Mine. According to this interpretation, the

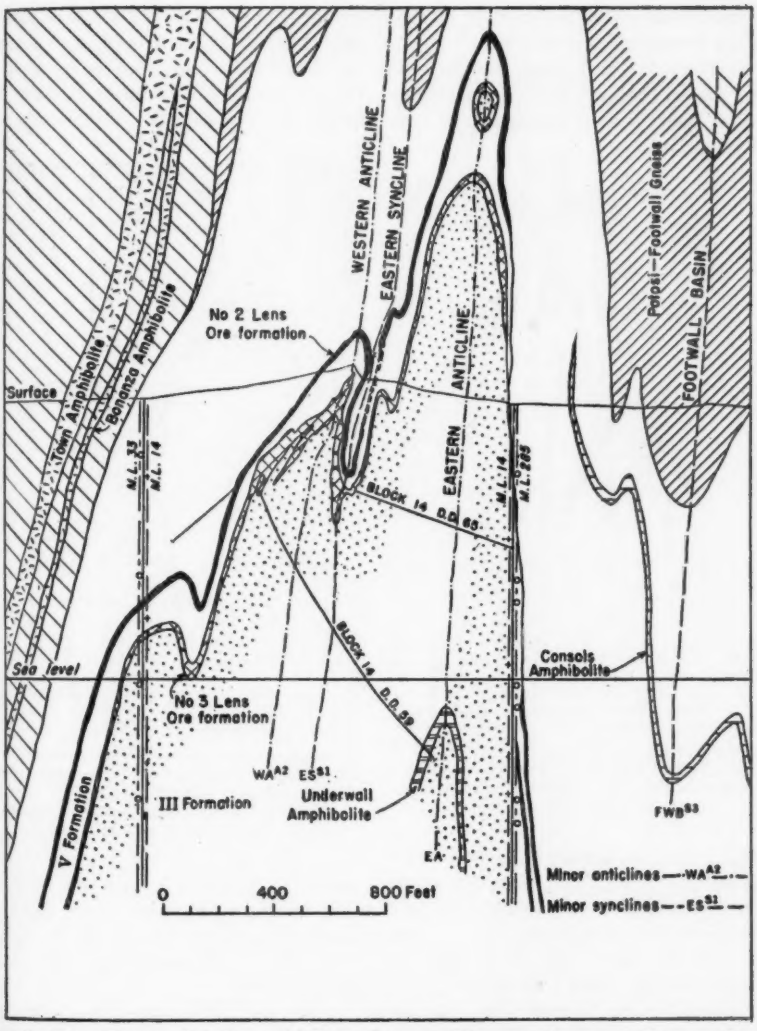


FIGURE 9.—CROSS SECTION 7–8, BLOCK 14 MINE, SHOWING WESTERN ANTICLINE, EASTERN SYNCLINE, AND EASTERN ANTICLINE

Eastern anticline has been elevated so far above the other structures and has become such a large fold that the Western anticline and Eastern syncline are now no more than small minor folds on its western leg. According to a second possible interpretation—that the ore-bearing structures are more easterly minor folds on the west leg of the Eastern anticline than any appearing in the British Mine—the Western anticline, Eastern syncline (and other mineralized folds there) have either died out or exist in depth down the eastern leg of the Eastern anticline as minor folds of that structure. In the discussion of the British fault, reasons are advanced against this interpretation.

Figure 13 illustrates in a highly simplified way the kind of changes just described. (In this sketch each structure is assumed to have a constant pitch. Actually this is not true.)

The chief evidence of the validity of this generalized interpretation is as follows:

1. The Western anticline and Eastern syncline are proved from the Zinc Corporation to the British fault by abundant structural and stratigraphic data.

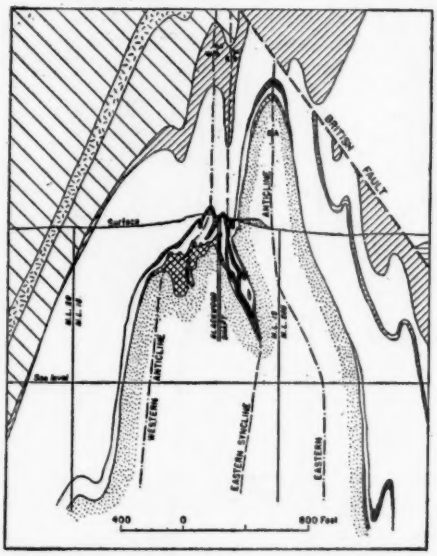


FIG URE 10.—CROSS SECTION, SOUTHERN PART OF BRITISH MINE (BRITISH 430N), SHOWING WESTERN ANTICLINE, EASTERN SYNCLINE, AND EASTERN ANTICLINE

2. No. 2 Lens ore formation where it forms the eastern limb of the Eastern syncline can be seen on the South Mine 1630-foot level to turn over eastward into an anticline and to dive underfoot. This interpretation is the only one that appears at all rational in this mine, the Zinc Corporation, the Central Mine, and the southern part of the B.H.P. Mine. The low-grade ore outcropping east of Wigg Shaft in the vicinity of Section 37 of the B.H.P. Mine can be accommodated satisfactorily only by this interpretation.

3. The old North Central Extended Shaft in M.L. 55 near the M.L. 11 boundary was sunk 700 feet before 1901. Old reports describe iron and manganese-stained lode material containing specks of silver chloride and silver bromide, but no payable lode. Another old shaft near the west boundary of M.L. 79 is shown on Jacquet's map (Jacquet 1894). A third, near the southwest corner of M.L. 80 put down by the Broken Hill Central Blocks Company in 1889, is reported to have struck "highly mineralized

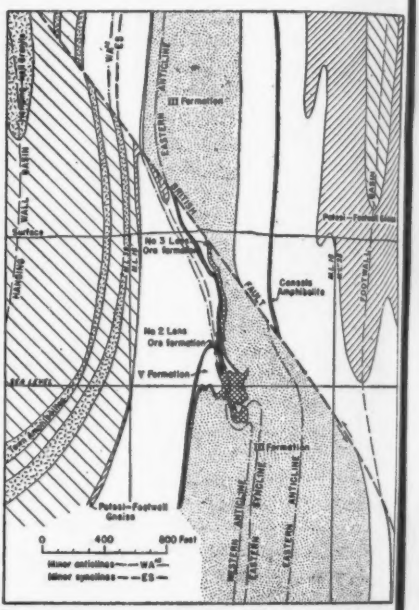


FIGURE 11.—CROSS SECTION, NORTHERN PART OF BRITISH MINE (BRITISH 1700 N), SHOWING WESTERN ANTICLINE, EASTERN SYNCLINE, AND EASTERN ANTICLINE

country". (These shafts are now covered by mine dumps). Probably they encountered poorly mineralized No. 3 Lens ore formation where it forms the eastern limb of the Eastern anticline.

4. Just as, in the southern part of the line of lode, it is very difficult to interpret the ore horizons as extending upward after they emerge from the Eastern syncline, so is it difficult to interpret them as doing anything else in the British, Junction, Junction North, and North Mines. Minor folds in both walls of the ore bodies in these mines suggest anticline to the east. And in the British Mine two strands of ore corresponding to No. 2 and No. 3 Lens ore formations extend upward.

5. The coarse garnet gneiss between the lodes

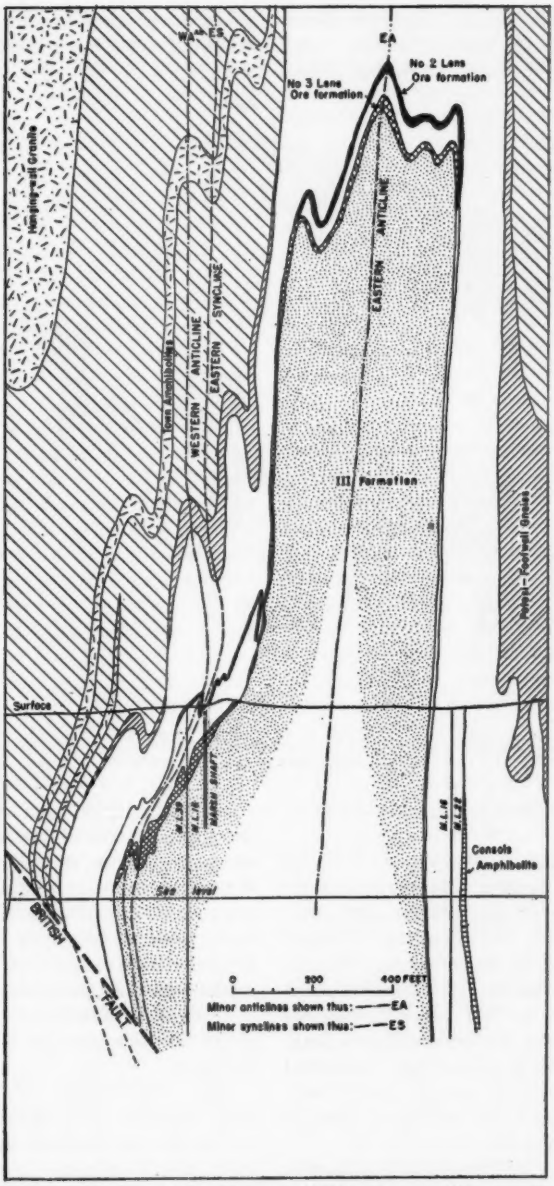


FIGURE 12.—CROSS SECTION, JUNCTION MINE (BRITISH 3100N), SHOWING WESTERN ANTICLINE, EASTERN SYNCLINE, AND EASTERN ANTICLINE

and the Potosi-Footwall gneiss east of the North Mine resembles the coarse garnet gneiss seen underground below No. 3 Lens ore formation.

6. The correlation of the Footwall gneiss with the Potosi gneiss as a single stratigraphic horizon (see "Stratigraphy") has much to rec-

ommend it. The lode horizons definitely underlie the Potosi gneiss in the Western anticline at the North Mine, and they also underlie the Footwall gneiss in the Footwall basin at the South Mine.

7. On the surface, the Potosi-Footwall gneiss in the Footwall basin is 1100 feet east of the North Mine Ore Bodies, 900 feet east of the Block 14 ore bodies, 250 feet east of the Central Mine ore bodies, and almost touches the Zinc Corporation ore bodies. This steady convergence southward in itself, strongly suggests that the intervening Eastern anticline is pitching south (relative to the ore bodies) and that it is probably becoming a progressively smaller feature on the east leg of the Western anticline the farther south it goes.

8. The Hanging wall granite in the Hanging wall basin on the contrary converges on the lode northward, a fact suggesting that the Western anticline, a prominent structure at the south end, is pitching north (relative to both the Hanging wall basin and Eastern anticline) and becoming a progressively smaller feature on the west limb of the Eastern anticline the farther north it goes.

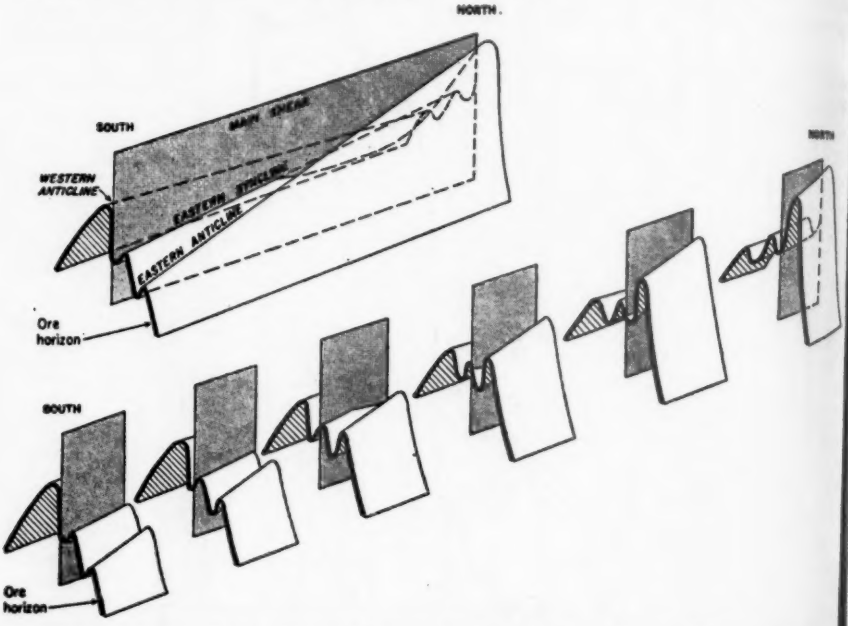


FIGURE 13.—SIMPLIFIED ILLUSTRATION OF WESTERN ANTICLINE, EASTERN SYCLINE, EASTERN ANTICLINE AND MAIN SHEAR RELATIONSHIP

9. The transition from dominant Western anticline with subordinate Eastern anticline to dominant Eastern anticline with subordinate Western anticline is indicated to be gradual and relatively harmonious by the detailed behavior of minor folds. (*See* discussion of "Ore-Bearing Folds" and various longitudinal sections showing pitch lines.)

Composite behavior of major folds.—The composite behavior of major folds is summarized on Plate 1.

Belt of attenuation and main shear.—The central portion of the field between the Hanging wall basin and Footwall Basin is a complex anticline with dominant but not continuous south pitch. Focussing attention on the ore-bearing formations, the Eastern syncline appears as a deep crease dividing this complex anticline into the Western anticline and the Eastern anticline, but a crease which starts at

the north end of the field on the west side of the large anticline and ends up at the south end of the field on the east side of the large anticline, crossing the larger structure at a very acute angle (Fig. 13).

The tightest folding and greatest stretching suffered by the ore-bearing formations anywhere within the complex anticlinal region is obviously confined to a narrow belt about 150 feet wide which coincides in a general way with the crease that is the Eastern syncline. Actually the belt extends chiefly along the east side of the Western anticline and frequently, but not invariably, includes the Eastern syncline. At the north end of the field, where the Eastern syncline has lost its significance the belt occupies the west limb of the Eastern anticline. The belt has no clearly defined limits but almost any cross-section of the lodes reveals that the westernmost minor folds are fairly open whereas the minor folds near the footwall of the lodes are tight and often greatly elongated. This belt of most intense plastic deformation is of supreme importance. The Broken Hill ore bodies were localized where this structure intersected the favorable beds of No. 2 Lens and No. 3 Lens ore formations. Whatever minor folds happen to be involved in this belt are greatly attenuated although the same minor folds elsewhere may be very open.

The "main shear" occurs within the belt of attenuation. The narrow, steep, tabular ore above the "broad lodes" in the Zinc Corporation and South Mines, which is termed the "narrow lode", is structurally a smeared out anticline of No. 2 Lens ore formation. This structure, the long, downward projecting, and greatly attenuated syncline of No. 3 Lens ore ("L" syncline) in the Central Mine below the "broad lodes", and the stretched ore-bearing eastern limb which connects the Western anticline with the Eastern syncline in the South Mine are all manifestations of the main shear. Where later faulting along the structure has not schisted the rock, the main shear would be very difficult to recognize had mineralization not made it conspicuous. Along the footwall side of the North Mine ore bodies and extending above them to the surface is a similar plastic shear along which very considerable rock movements must have occurred; yet here the shear is not conspicuously marked by mineralization, and it is not so easily identified.

The main shear is not, however, one continuous plane throughout the line of lode. By "main shear" is meant merely the most conspicuous (plastic) shear plane at any place within the belt of attenuation, whether or not it has been accentuated by later shearing during the period of faulting and buckling. Actually the main shear occupies at least three planes offset *en echelon* between The Zinc Corporation and the British Fault. The main shear thus coincides first with one part of the folded structure and then with another. For example, from about McBryde Shaft in the B.H.P. Company property to some unknown distance into the South Mine, No. 3 Lens ore formation is stretched downward into a very tight syncline ("L" syncline). A short distance north of McBryde Shaft, however, "L" syncline rapidly recedes upwards, and "M" syncline suddenly becomes the dominating structure. "M" syncline assumes prominence because a new shear plane (the "East Vein"), offset en echelon to the east and north and coinciding with "M" syncline, takes up the burden of most intense movement at the place where the old main shear coinciding with "L" syncline ceases to be the locus of such movement. The new main shear continues as "M" syncline, but with no such extreme elongation on it as heretofore until the British Mine is reached. In the vicinity of Howell Shaft the main shear takes another abrupt jump to the east and continues northward as the British Mine "East Vein". "M" Syncline is abandoned, the new main shear coinciding now with "P" Syncline. So far the discussion has been confined to the relationship existing between the main shear and minor folds involving the underwall of No. 3 Lens ore formation. The cross-sections show that the main shear does not continue up the axial plane of any minor fold and so occupy the same structural position at say the overwall of No. 3 Lens ore formation or the underwall of No. 2 Lens ore formation. Instead it cuts through various minor folds to which it is inclined at an acute angle. The transgression of structures by the main shear is much more abrupt vertically than it is along the strike.

The continuation of the belt of attenuation

southward is in doubt, probably chiefly because of a lack of outcrops. The faulted segment of the belt north of the De Bavay Fault has not been recognized with certainty because of the very complex geology in this region. Over what distance north and south the twisting movement between Western anticline and Eastern anticline was effective in producing the belt of attenuation cannot be determined. This particular strain must have been very local in a regional sense. Other similar belts of attenuation which may (or may not) have served as feeder channels through which ore solutions were conducted to favorable formations undoubtedly exist, but their recognition from surface outcrops is a different matter.

Several places have been suggested to the mining companies as possible new belts of attenuation which may intersect No. 2 Lens and No. 3 Lens ore formations.

Ore-Bearing Folds

Method of analysis[18] *and definition of terms.*—The ore-bearing folds, which are minor folds comprising the Eastern syncline and portions of both the Western anticline and Eastern anticline, have been analyzed in great detail. (1) All exposures were mapped for structural features, rock types, and ore mineralogy, and all drill core was logged for the same features. (Mapping was done on a scale of 30 feet, 40 feet, or 60 feet to the inch); (2) These data, together with pertinent assay data, were plotted on 100 scale cross-sections and plans, the formations were colored with distinctive colors, and structural outlines where data permitted; (3) Lines were drawn on plans and cross-sections to show the traces of the axial planes of the separate folds, and these were adjusted on plans and cross sections to give agreement. The earlier structural picture was revised as required; (4) Plotted in longitudinal projection were all known "axial line points", the points on plans and sections where the axial planes cut the underwall and overwall of ore-bearing formations. By connecting these points longitudinal projections of axial lines were obtained. Plans and cross-sections were again revised where necessary and permissible to obtain agreement with the requirements of the longitudinal projection; (5) The axial lines were then plotted in plan projection in much the same manner as described for the longitudinal projection; (6) Using chiefly the longitudinal and plan projections of axial lines; the structures were projected beyond present mine workings where the need arose; (7) Each axial plane and axial line was given a temporary number; (8) Finally structures were correlated according to the best evidence and a consistent numbering system adopted for axial planes on axial lines.

The term "first-order fold" describes an ordinary fold, however complex, whose axial plane has not been notably deformed by a continuation of the folding movements, though it may be deformed by post-folding buckles or faults. "Second-order fold" describes a fold whose axial plane has been folded by a continuation of the same rock movements that produced the first-order fold. A second-order fold is thus a folded fold. It is not always possible to distinguish between the two; they ordinarily have approximately the same pitch. Post-folding buckles, on the other hand, normally have very steep pitch and can usually be distinguished from folds except where the latter also have steep pitch.

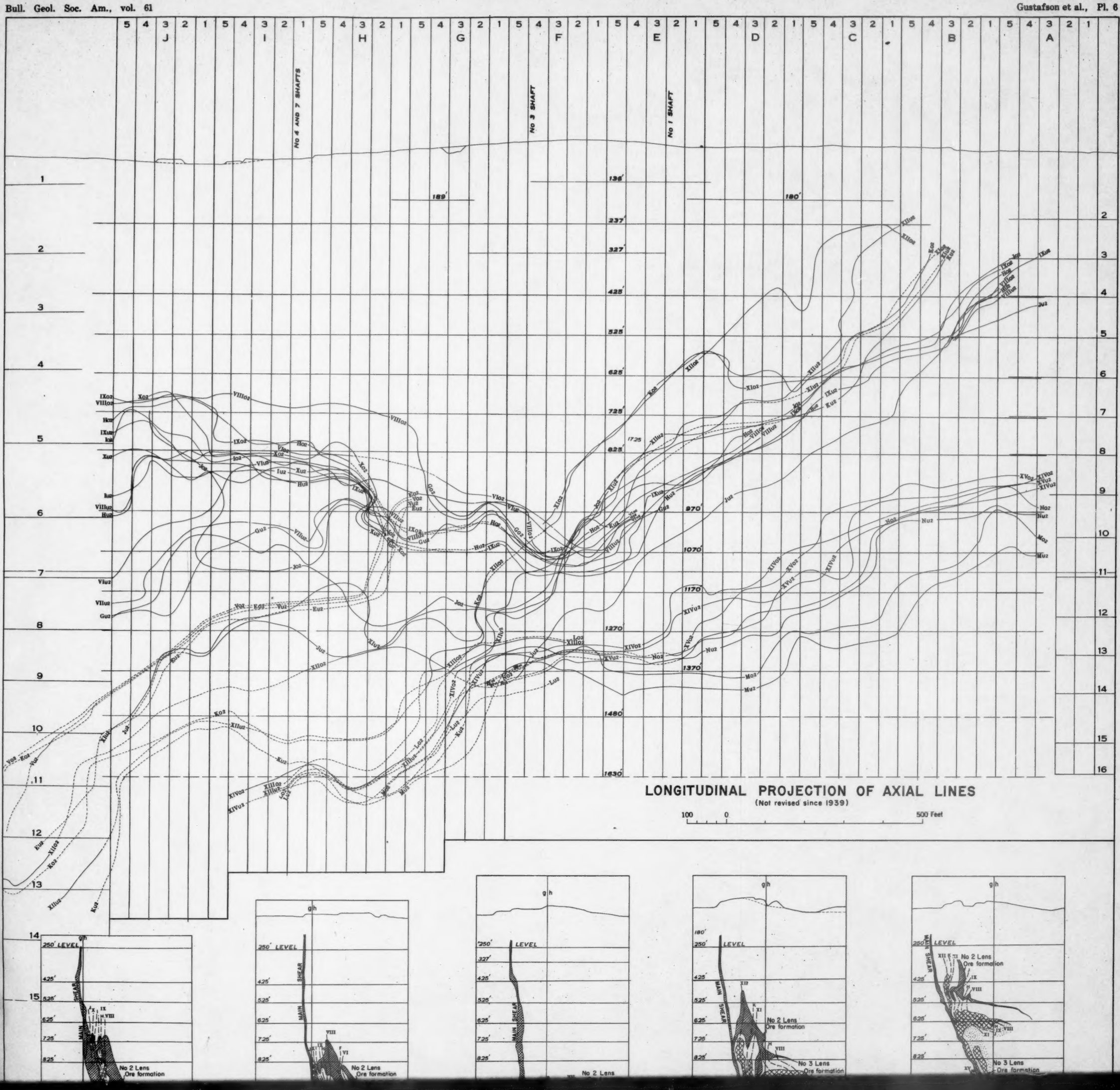
Tabulation of minor folds.—Minor ore-bearing folds were tabulated and correlated with major folds on two charts. The system of notation used is as follows:

(1) Axial planes of anticlines are numbered from west to east with Arabic numerals north of the British Fault and with Roman numerals elsewhere, and are portrayed on plans and cross-sections thus —·—·—·—·

(2) Axial planes of synclines are lettered from west to east with small letters north of the British Fault and with capital letters elsewhere, and are shown on plans and cross-sections thus - - - - - -

(3) Points on axial lines are designated by the letter or number of the axial plane to which they belong, by an "O" or a "U" according to whether they are overwall or underwall points.

[18] This procedure was not followed in the orderly manner here suggested. Most places were remapped at least once (some as many as three times), and the structural interpretation was constantly revised as knowledge and technique improved. In a final review the method of steps (3) to (8) was re-applied to the whole line of lode.



LONGITUDINAL PROJECTION OF AXIAL LINES

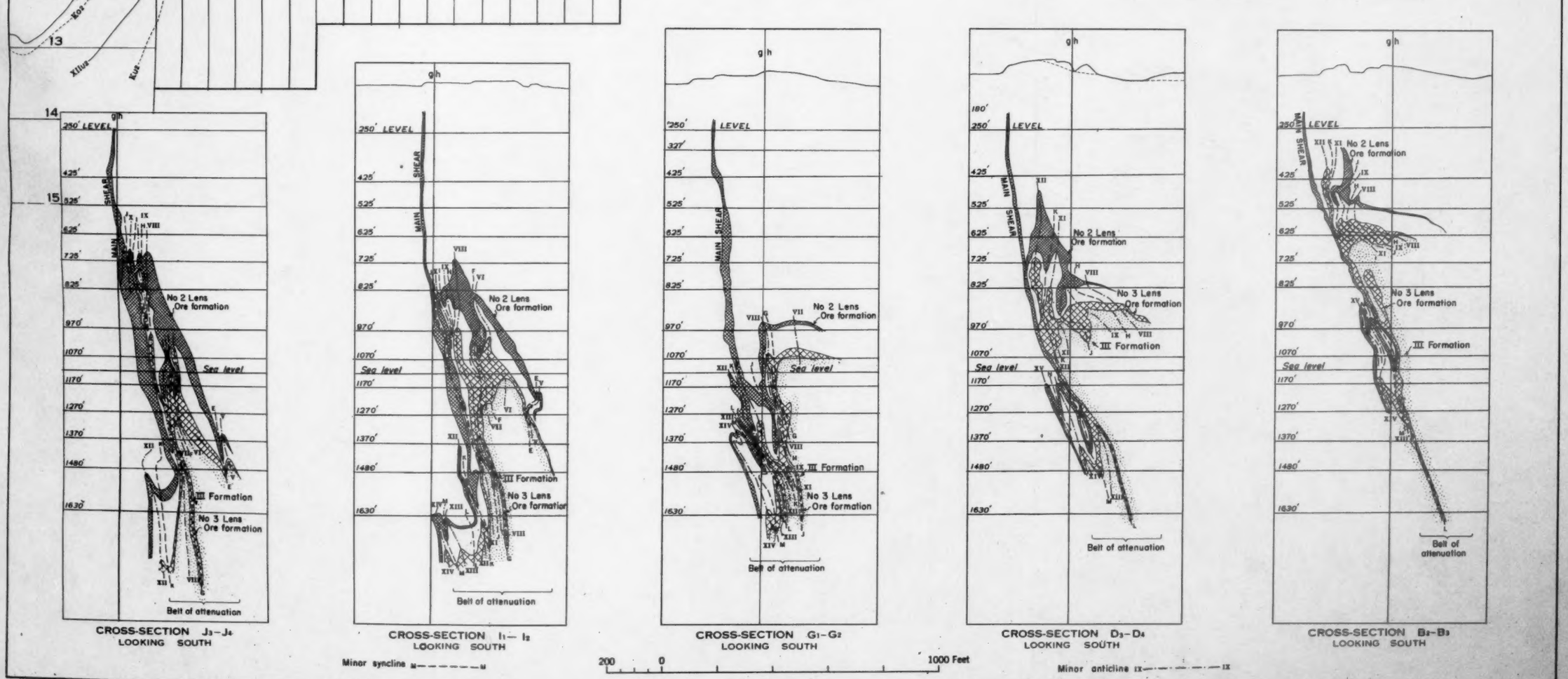
(Not revised since 1939)

100 0 500 Feet

LONGITUDINAL PROJECTION OF AXIAL LINES

(Not revised since 1939)

100 0 500 Feet



LONGITUDINAL PROJECTION OF AXIAL LINES WITH EXPLANATORY CROSS SECTIONS, BROKEN HILL SOUTH LIMITED

ed by a "2", or a "3", depending on whether hey are referred to No. 2 Lens ore formation r No. 3 Lens ore formation. Thus IXU3 is a oint on the underwall of No. 3 Lens ore rmation in No. IX anticline.

The discussion accompanying each album of 0 scale plans supplied to the companies called ttention to the more conspicuous uncertainties the interpretation.

Plate 6, a longitudinal projection of some of e axial lines in the South Mine, illustrates the aracter of the axial-line study of pitch.

Other Folds

Numerous minor folds which make up the ajor folds are portrayed on the various plans d cross-sections. For example, the Footwall asin is composed of at least the following inor synclines and anticlines: FWB^{s1}, FWB^{s1}, WB^{s}, FWB^{s3}, FWB^{s2}, FWB^{s3}, FEB^{s4}.

Locally a minor fold becomes so big as to be reality a new major fold-the Imperial Ridge nticline, for example, at Imperial Ridge. This ructure farther south is merely a small minor ld on the west flank of the Eastern anticline. milarly, the minor fold FWB^{s3} is believed to ow progressively larger south of the Zinc orporation New Main (Freeman) shaft until becomes a major structure and is recognized the Alma anticline, whereas the fold com-ising the Alma anticline farther north, AA^{s1}, s apparently grown smaller and become erely a minor fold on the flank of the Alma nticline.

Mechanics of Folding

Plastic folds and plastic shears.—Projections d geological interpretations of the intricate e-bearing folds will be made with greater nfidence and more accuracy if the nature of e folds and their method of formation is derstood. The shapes of the folds reveal that e rocks of the district acted under compression e soft plastic materials. Rock was squeezed ay from the places of greatest pressure such the limbs of folds and flowed into places of ast pressure such as the crests and troughs of lds. Such rock flowage can be accomplished in cks like granites and gabbros only with the aid of extensive recrystallization. The metamorphic minerals of the gneisses are minerals stable at high temperatures and great pressures characteristic of great depth in the earth's crust. It is not unlikely that these rocks were overlain by from 10 to 20 miles of rock at the time of folding.

Places like the belt of attenuation where the greatest escape of material took place can be regarded as "shear zones" provided that *plastic* shear rather than granulation is understood. The rock in plastic shear zones need not look any more broken or schisted than elsewhere. Frequently it does but only because of later fault movements in these old zones of weakness.

Main shear and the belt of attenuation.—The development of the belt of attenuation between the Eastern and Western anticlines can be readily explained if the relationship between these two folds is clearly understood (*see* discussion under "Major Folds"). Figure 13 and Plate 1 clearly indicate the strong twisting movement that must have occurred during folding to produce these two divergent anticlines. This movement was in large measure confined to the steep narrow belt between the two structures that is now recognized as the belt of attenuation.

The axis of rotation (Pl. 1) occupies the region between Weatherly shaft in M.L. 11 and Wilson shaft in M.L. 13 of the B.H.P. mine. No satisfactory correlation can be made between the prominence of the main shear as an ore-bearing structure and its position relative to the axis of twisting. At Weatherly shaft the main shear and belt of attenuation are well developed. Just north of the axis of rotation, however, between Dickinson shaft and the British Mine where the displacement was small, the belt of attenuation and main shear are least well developed. In the Zinc Corporation at the south end of the field, on the other hand, where one direction of maximum movement (with east side down) existed, the belt of attenuation and the main shear find their best development. Likewise in the North Mine at the north end of the field where the other direction of maximum movement (with west side down) existed, the belt of attenuation is also well developed and a main shear—though virtually unmineralized—is clearly in evidence.

An outstanding characteristic of the footwall of the main shear at the southern end of the field is the rather frequent occurance of nearly vertical, somewhat rounded hollows and ridges in the contact between ore and wallrock. They

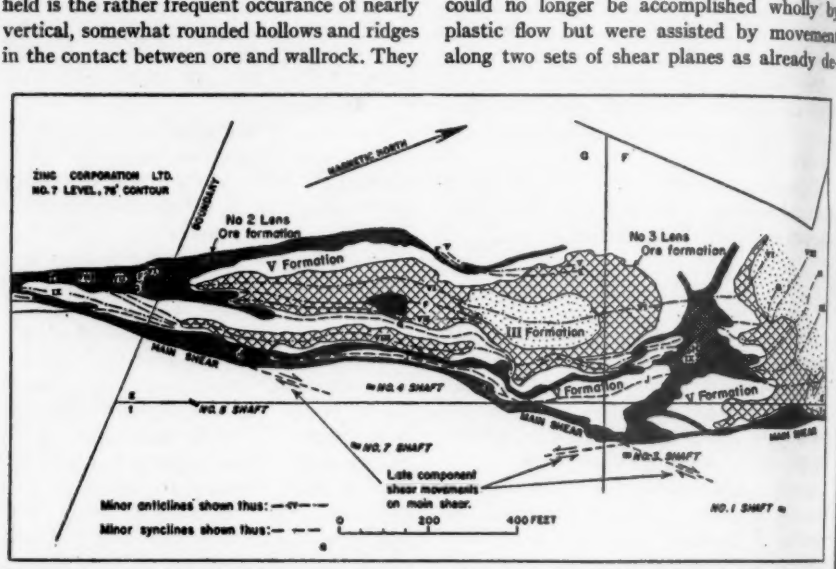


FIGURE 14.—SOUTH MINE 1070 LEVEL AND PORTION OF ZINC CORPORATION NO. 7 LEVEL 76 FT. CONTOUR

developed) was apparently lessened in the latter stages. Further attempts to elongate vertically could no longer be accomplished wholly by plastic flow but were assisted by movement along two sets of shear planes as already described. Possibly belonging to the east-dipping shear direction are the "East Vein" shears of the B.H.P. Company and British Mines (Figs. 15, 16). Each structure was obviously the locus of plastic shearing (and probably also of faulting) after the main folding pattern was already established.

vary in size but are characteristically 2 to 5 feet from hollow to hollow and 20 feet or more long. Some of these are almost certainly "buckles" due to post-folding movements and as such are described. It may well be, however, that many of these ridges and hollows constitute mullion structure produced by the essentially vertical movement on the main shear during folding as a result of the twisting motion which here depressed the Eastern anticline and elevated the Western anticline.

The main shear in the southern part of the field appears to have been essentially vertical in cross-section (as were the axial planes of folds) until a very late stage in the folding. Locally, however, during the final compression, two sets of shear planes appear to have developed at an acute angle to the old direction, and overthrusting movements on these occurred. Some second-order folds were doubtless developed at the same time by the same movements. (Figs. 14, 29). The perfect plasticity which characterized the rocks during the major part of the folding period (during which the relief was vertical and no true shear planes were

Relation of minor folds to major folds and to the belt of attenuation.—Casual inspection of successive cross-sections of the ore bodies from the Zinc Corporation to the British Mine reveals a rough constancy of fold pattern wherein the Western anticline and Eastern syncline are ever present although changing in shape from place to place. Detailed analysis of the small minor folds which make up the Western anticline has, however, revealed a relationship between minor folds and major folds which, to our knowledge, has never been described in geological literature.

Consider Figures 17 to 22 inclusive in the numerical order, i.e. from north to south in the direction of predominant pitch. Watch first axial line points VIIIU3 and VIII03. These first occupy a small wrinkle out on the west limb of the Western anticline. Southward the

points progressively cross over the crest of the Western anticline and migrate down the eastern side of the main arch until they come within the influence of the belt of attenuation. Suddenly the anticline changes from a mere wrinkle to a long attenuated structure. Now watch points GU3, JU3, XIIO3, and others. The

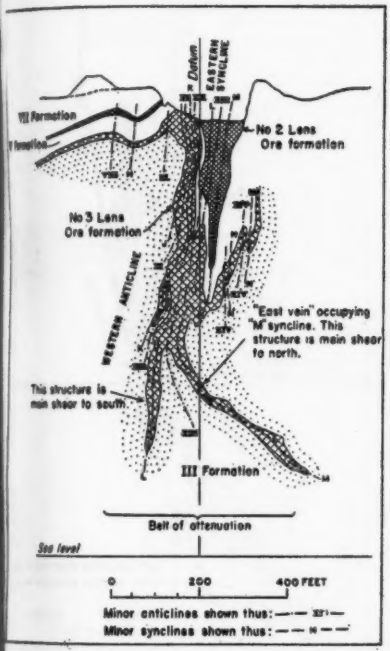


FIGURE 15.—B.H.P. SECTION NO. 35, SHOWING "EAST VEIN"

same spiralling form of migration up, over, and down from west to east is shown by each minor fold as it progresses southward. And each in turn may apparently begin as a small wrinkle which assumes sudden prominence as it enters the belt of attenuation. In the case of Anticline III, there is a strong suggestion that it passed through the main shear and emerged as a diminished structure on the eastern side, though exploration has not yet gone deep enough to permit a decisive statement. Careful search will reveal similar, if not so striking, examples of migration of minor folds in the cross-sections of the other mines.

Two large charts which correlate major and minor folds and show diagrammatically the angular relationship between minor and major folds existing at the underwall of No. 3 Lens ore formation and at the overwall of No. 2

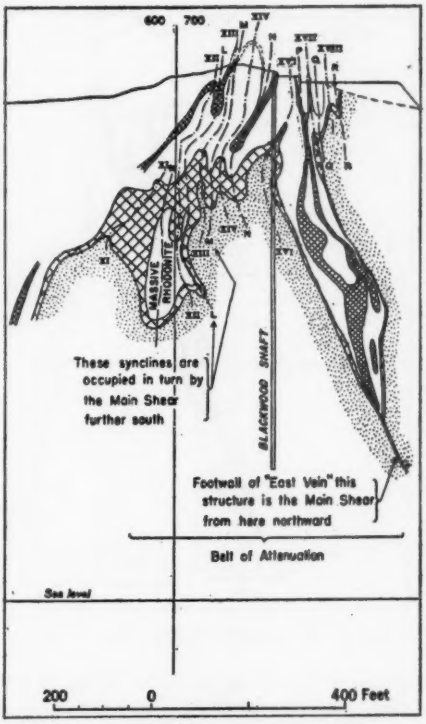


FIGURE 16.—BRITISH MINE SECTION 430, SHOWING "EAST VEIN"

Lens ore formation for the whole line of lode—included in the report by Gustafson (1939) but not in this paper—indicate the considerable extent to which the transgression of minor structures by the belt of attenuation is accomplished by sudden jumps rather than by progressive angular encroachment. They also reveal that although more and more easterly minor anticlines occupy the highest place in the Western anticline as one goes north, there are numerous small setbacks during this change. To some extent second-order folding is responsible for these setbacks.

This migratory character of "minor folds" in relation to "major folds" is also possessed

by the "major folds" in relation to folds of the next higher degree of magnitude, as indicated by the relative behavior of the Western anticline, Eastern syncline and Eastern anticline

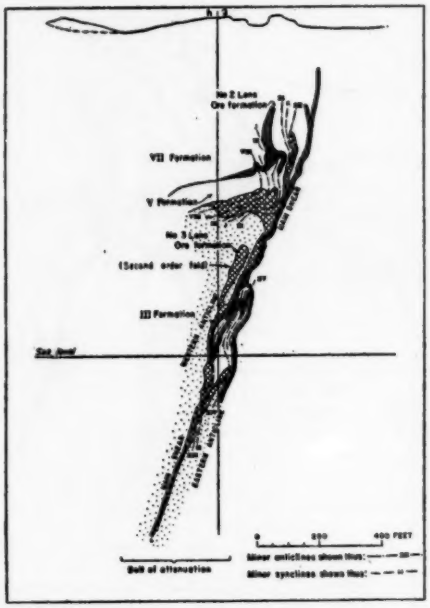


FIGURE 17.—SOUTH MINE, SECTION B2B3

discussed under "Major Folds" (Figs. 13, 23). One explanation of this angular relationship is: (a) the Eastern syncline developed as an indentation at the top of a large anticline very early in folding; (b) as squeezing continued, because of torsional stress, the eastern half of the anticline (Eastern anticline) rolled up into a large fold at the northern end of the field whereas the western half (Western anticline) developed into the major structure to the south; (c) thus the early syncline identation maintained its identity throughout folding, serving as a locus of rotational plastic shear and now being identified as the belt of attenuation.

Second-order folds.—The distribution and orientation of local stresses within the Western anticline and Eastern syncline (including the belt of attenuation) must have been not only a very complex but a constantly changing system. Certain elements can, however, be analyzed.

In the discussion of "The main shear and the belt of attenuation", it was postulated that, at a late stage in folding, vertical relief was

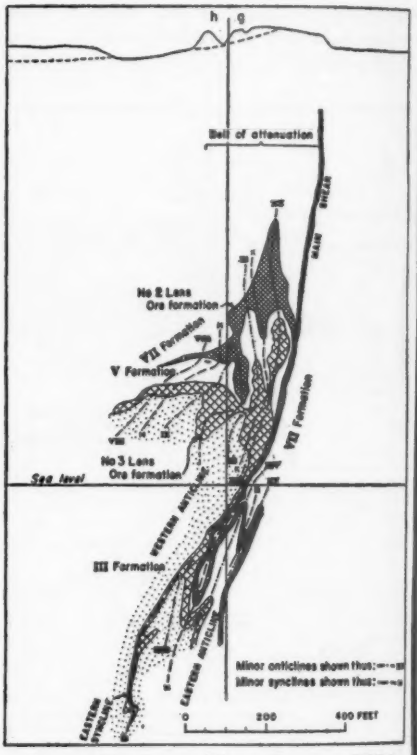


FIGURE 18.—SOUTH MINE, SECTION D3D4

accomplished with the aid of two sets of plastic shear planes. Outside the belt of attenuation, the rock movement during this late stage was one of broader warping or second-order folding rather than of plastic shearing confined to any single plane. Nevertheless, two directions of movement comparable and probably related to the two plastic shear directions are indicated by the second-order folds (Figs. 24-28). The commonest and largest second-order folds are those indicating "west side up"; those less common and generally smaller indicate "east side up"

Not all second-order folds, however, can be quite satisfactorily related to the very late stage of folding during which the two plastic

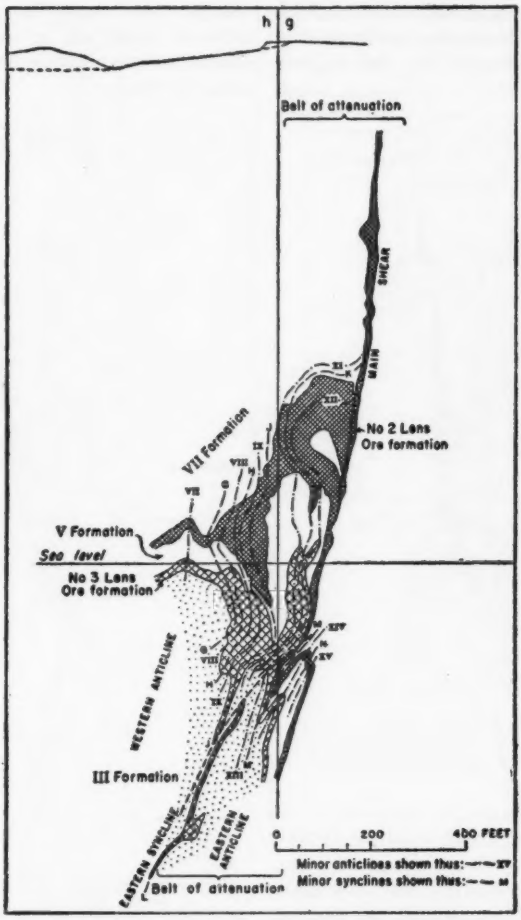


FIGURE 19.—SOUTH MINE, SECTION E5F1

shear planes operated. For example, the important second-order fold in "L" syncline (of No. 3 Lens) in Fig. 26 with its nearly vertical dip may belong to the earlier stage of folding when plastic movement on the main shear occurred, but before that structure was deformed by the younger shears.

Changes of pitch.—The pitch line of the ore bodies in a general way describes a flat arc plunging southward at the Zinc Corporation, northward at the North Mine. Local wobbles and sudden reversals of pitch are frequent. Reference to the various longitudinal sections will show very marked divergence in the pitch lines of both minor folds and major folds.

Changes of pitch of either a single minor fold or of a whole group of folds are fairly common and are extremely important when projecting ore bodies. Both the North Mine and the Zinc Corporation to-day are paying dividends from ground obtained at low cost because of the pessimism of former holders born directly of a lack of understanding of pitch.

Pitch changes in the ore bodies have been brought about by several influences—

(1) "Normal" changes of pitch unaccom-

panied by any marked deviations in the axial planes of the folds. The reason for the position of a high place in the axial lines due to pitch changes in the Central Mine opposite the main shaft are chiefly due to this cause (Fig. 27), although a steep buckle here may be a contributory factor.

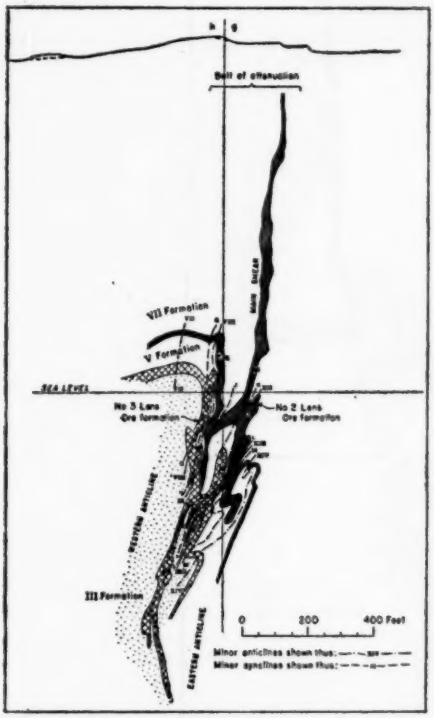


FIGURE 20.—SOUTH MINE, SECTION G1G2

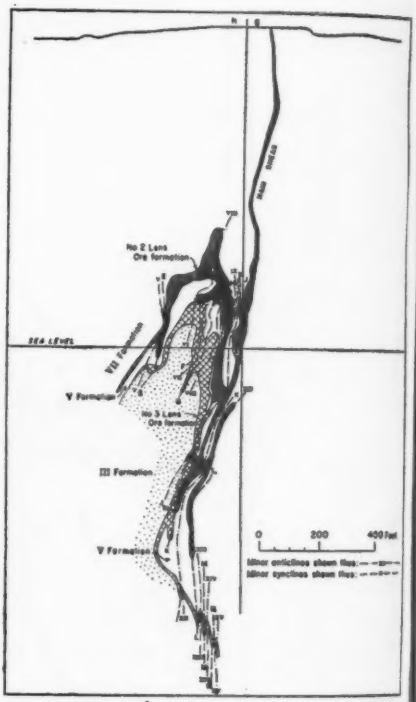


FIGURE 21.—SOUTH MINE, SECTION H.H2

reversals of this kind is as obscure as the reason for the location of an anticline. No essential differences detected in the shapes of the folds could be regarded as typical of axial line peaks rather than of axial line troughs or of intermediate axial line slopes, nor was any mechanism other than longitudinal bending of the folds suggested for pitch changes of this type. The sudden pitch change at the B.H.P. Company—Block 14 boundary is of this type. So also in part at least are the major pitch changes in the South Mine. Here, however, other influences—buckles and second order folds—complicate the issue.

(2) Pitch changes due to strong local development of second-order folds. The pitch

(3) Pitch changes due to post-folding deformation. The buckling of the rocks at the South Mine—Zinc Corporation boundary is probably at least partly responsible for the local vertical pitch at this place. Another prominent buckle in the South Mine (at G1 on the 1370 level) appears to have caused the pitch of the more easterly ore-bearing folds to steepen. In the Central Mine opposite the Kintore Shaft and in the British Mine near Howell Shaft, buckles accompany pitch changes. Whether buckling produced these pitch changes or whether buckling was most easily accomplished at places of sudden pitch change is still in doubt.

The most abrupt pitch change along the line

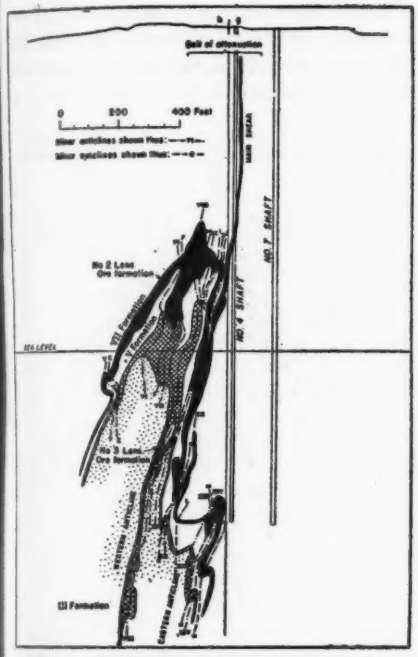


FIGURE 22.—SOUTH MINE, SECTION I_1I_2

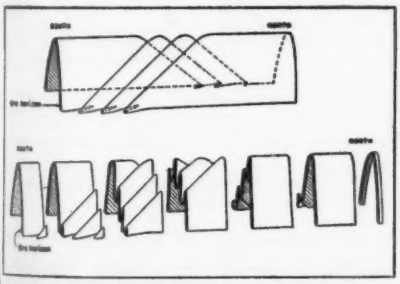


FIGURE 23.—SIMPLIFIED PORTRAYAL OF ANGULAR RELATIONSHIPS BETWEEN MINOR AND MAJOR FOLDS IN SOUTH MINE

of lode, and one of considerable magnitude, is that caused by drag on the British Fault. Figure 29 illustrates a local severe pitch change in the Zinc Corporation mine.

Variable shapes of different rocks in the same folds.—A striking characteristic of the fold pattern is that different rock layers have totally different shapes in the same folds (Figs. 19–25). What is a very prominent fold in the underwall of No. 3 Lens ore formation may be a smaller fold in the overwall of this same formation. Again, a predominant fold in the underwall of

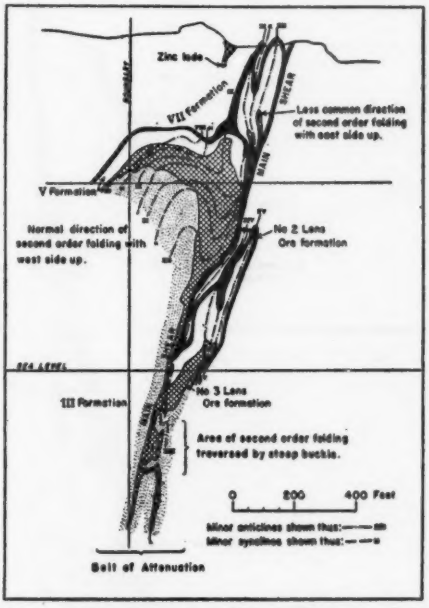

Zinc lode
VII Formation
Less common direction of second order folding with east side up.
V Formation
Normal direction of second order folding with west side up.
No 2 Lens Ore formation
No 3 Lens Ore formation
III Formation
Area of second order folding traversed by steep buckle.
0 200 400 Feet
Belt of Attenuation

FIGURE 24.—CENTRAL MINE, SECTION 5–6, SHOWING SECOND-ORDER FOLDING

No. 3 Lens ore formation may be a smaller fold in the overwall of No. 2 Lens ore formation. Again, the minor fold which constitutes the main underwall of the Western anticline as outlined by No. 3 Lens ore formation frequently does not constitute the main underwall of the Western anticline as outlined by No. 2 Lens ore formation in the same cross section.

Even more striking is the lack of concordance between the folds as outlined by the zinc lodes and as outlined by the lead lodes in the Zinc Corporation mine. Consider the long upward-extending limb of zinc lodes (Fig. 29) in relation to the narrow lead lode ("main shear"). It seems fairly certain that the "main shear" here is a tightly smashed anticline of No. 2 Lens ore formation which was replaced by ore to form the "narrow lead lode", yet both the eastern

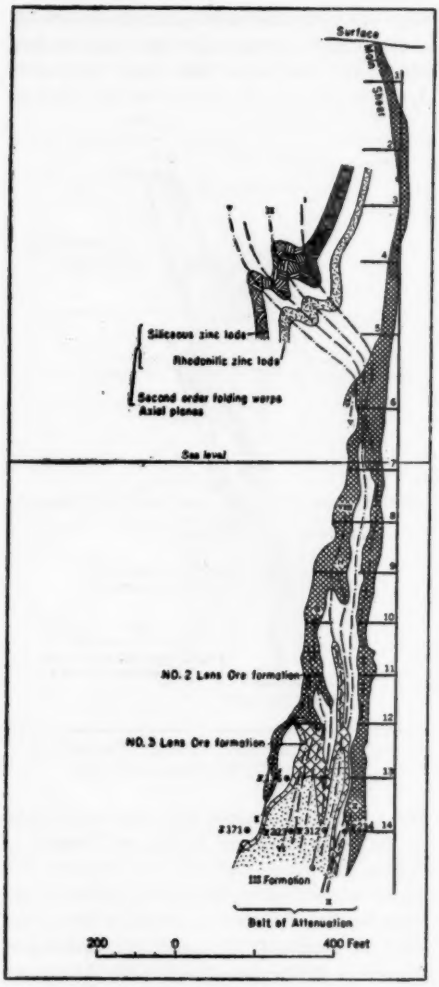


FIGURE 25.—ZINC CORPORATION, SECTION 10, SHOWING SECOND-ORDER FOLDING

limb and the nose of this anticline are missing in the stratigraphically higher horizons comprising the zinc lodes. On the other hand, No. 3 Lens ore formation does not appear to be involved in this structure at all.

Cross sections reveal that in general the zinc lode formations were more competent than the lead lode formations; at least they were less complexly crumpled.

Differences in strength of competency do not however, explain all differences in shape between rock formations, because what appears to be the competent rock in one place appears to

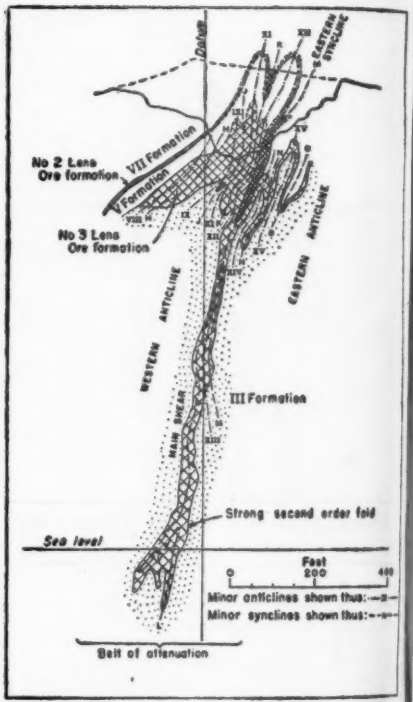


FIGURE 26.—BROKEN HILL PROPRIETARY SECTION 49, SHOWING SECOND-ORDER FOLDING

be the incompetent rock in another. A partial explanation lies in the angular relationship existing between minor folds and the belt of attenuation which permits the portion of a fold occupied by No. 3 Lens ore formation to be drawn out in the belt of attenuation, whereas the portion of the fold occupied by No. 2 Lens ore formation remains outside the belt of attenuation. In general, however, it appears that local stress differences were relieved locally and immediately by the very nearly perfect plastic flow of whatever rock was nearest.

Some structures, for instance that portrayed

by Figure 30, with a long attenuated downward projecting syncline, are difficult to understand mechanically if those rock formations portrayed are alone considered. Very likely, however, the formations at different places in the same structure. They are still more unreliable for estimating the distance in some other structure, as for example the Footwall basin.

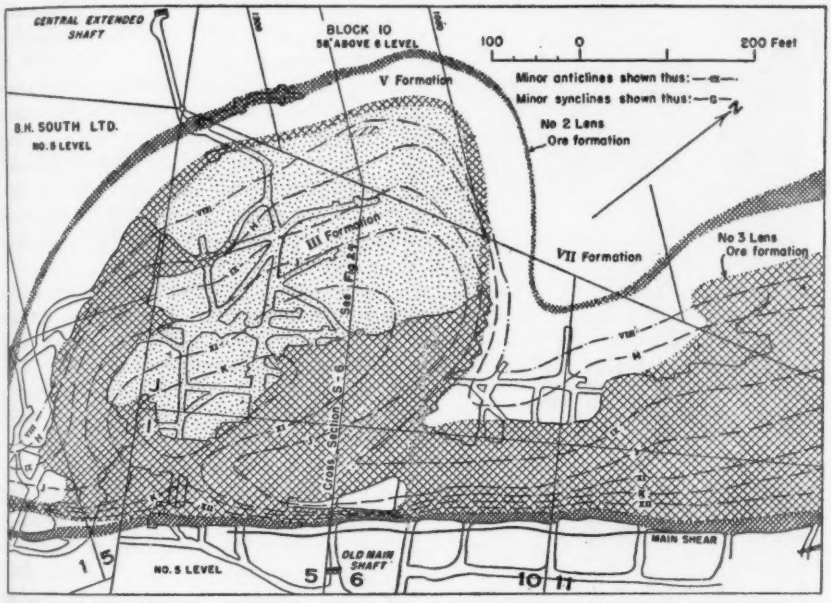


FIGURE 27.—PORTION OF CENTRAL MINE NO. 5 LEVEL, SHOWING SECOND ORDER FOLDING

overlying thick and comparatively strong layers of Hanging wall granite and Town amphibolites determined the shapes of the larger folds, and the softer, more plastic sedmients shown in the illustration were forced to accommodate themselves as best they could to the conditions imposed by their more competent neighbors.

Variable shapes of the same rocks in different folds.—The extreme variation in amount of packing in the noses of folds makes it impossible to estimate accurately the vertical distance separating any two stratigraphic horizons. The fact that the Potosi-Footwall gneiss is approximately 1000 feet above the No. 3 lens ore formation in the Western anticline at the North Mine and is nearer 2000 feet above at the Zinc Corporation illustrates how unreliable such figures are for estimating the distance between two

Major Faults

General discussion—The larger faults in the district and the numerous small but important buckles which warp the ore-bearing folds belong to a second main period of rock deformation that is chronologically intermediate between folding and ore deposition. During the folding period, strains permeated the entire body of the rock, and deformation was largely plastic flow through micro-faulting and recrystallization. Gneisses, not schists, were formed. The stresses of the second period found relief very locally and produced well-defined narrow belts of schisted or sharply flexed rock (Pl. 7, fig. 1). The yield was more by means of rupture and mechanical shear, although some rock flowage took place in the crush zones once they were established by fracture.

The pre-ore age of the major faults is estab-

lished by the following evidence[19]. (1) Although jointed and locally traversed by small post-ore faults, bodies of massive sulphides, lenses of garnet sandstone, and large masses of rhodonite

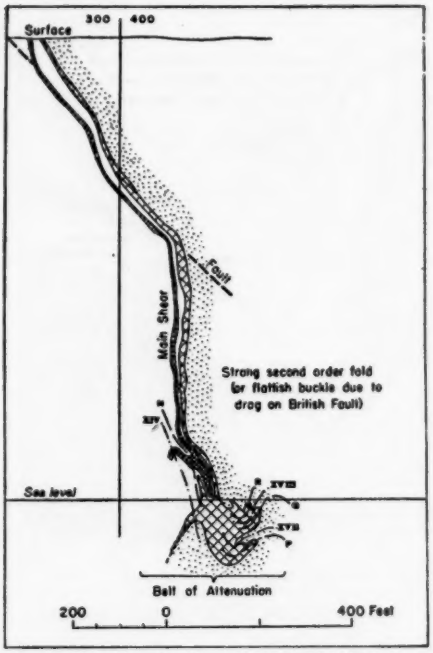


FIGURE 28.—BRITISH MINE, SECTION 18, SHOWING SECOND-ORDER FOLDING (OR FLATTISH BUCKLE DUE TO DRAG ON BRITISH FAULT)

are neither crushed nor conspicuously sheared even where they occupy strong buckles and

[19] Andrews (Andrews, *et al.*, 1922, p. 131) regards the faults as older than the lodes, but Kenny (1927, p. 545) believes the De Bavey Fault, at least, to be younger than the lodes. Mr. Kenny in conversation stated that he, like Andrews, considered the garnet-magnetite beds to be lodes, and, because they are clearly older than the fault, presumably the lead lodes are also. Evidence is given elsewhere in this report that these garnet-magnetite beds are not genetically related to the lead lodes.

zones of warp adjacent to the British Fault; (2) The steep bulges of ore on the main shear are the result of ore replacing previously buckled rock, not the result of ore deformed into these shapes. Yet the buckles were probably the result of the same stresses that caused the faults; (3) Lenses of undeformed sulphides in the Globe-Vauxhall crush zone clearly replace the mica schists. Had these sulphides been present during the development of this strong fault, they would have been greatly deformed; (4) The flat south-pitching buckles or dragfolds common north of the British fault may conceivably be related to the faulting period. In any case they are unquestionably replaced by the ore.

There are two main fault groups and a third subordinate one in the immediate district:

(1) Faults with strike approximating N50E to N70E (+); dip 80SE. Examples: Globe-Vauxhall crush zone, Morgan's fault. To the extent that it has participated in the second period of deformation, the main shear can also be classed as a fault of this group. Characteristics: Essentially parallel to the strikes (and axial planes) of rock formations. Marked by belts of mica schist containing occasional pegmatite lenses. Some strong first-group faults terminate faults of the second group but are nevertheless flexed by them; other smaller ones are offset by faults of the second group. Movement: North-west side has moved north-east; vertical component unknown but probably smaller than horizontal component. Apparent horizontal offset on Globe-Vauxhall crush zone probably about 3 miles (see footnote in discussion of Hanging wall basin).

(2) Faults with strike approximating N15W to N-S; dip, steep to E. Examples: De Bavay fault, British fault. Characteristics: Cut transversely across rock formations warping or offsetting them. Marked by belts of mica schist containing numerous lenses of pegmatite. Faults may end where they meet and merge

PLATE 7.—BROKEN HILL ROCK TYPES

FIGURE 1.—MICA SCHIST IN DE BAVAY FAULT

FIGURE 2.—SMALL STEEPLY DIPPING PEGMATITES PERPENDICULAR TO GNEISSOSITY, WEST OF LODE OUTCROP M. L. 15

These pegmatites are post-folding and are either the same age as the lodes or somewhat older.

FIGURE 1

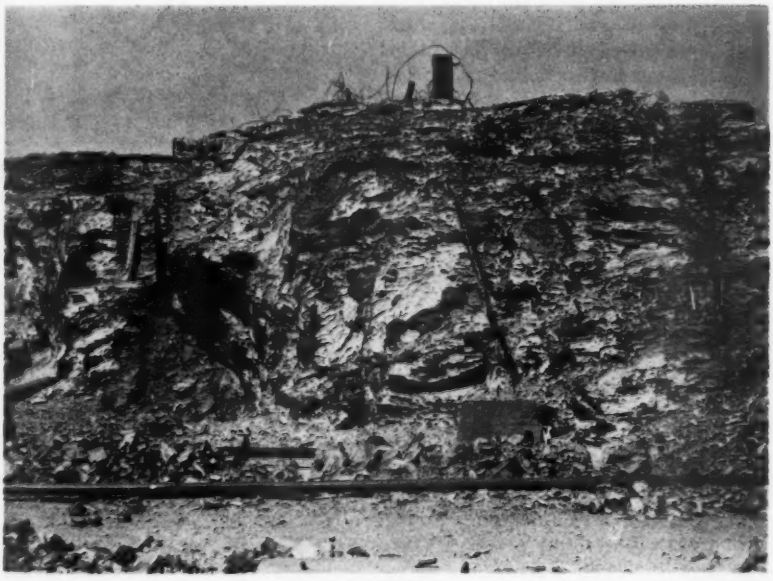


FIGURE 2

BROKEN HILL ROCK TYPES

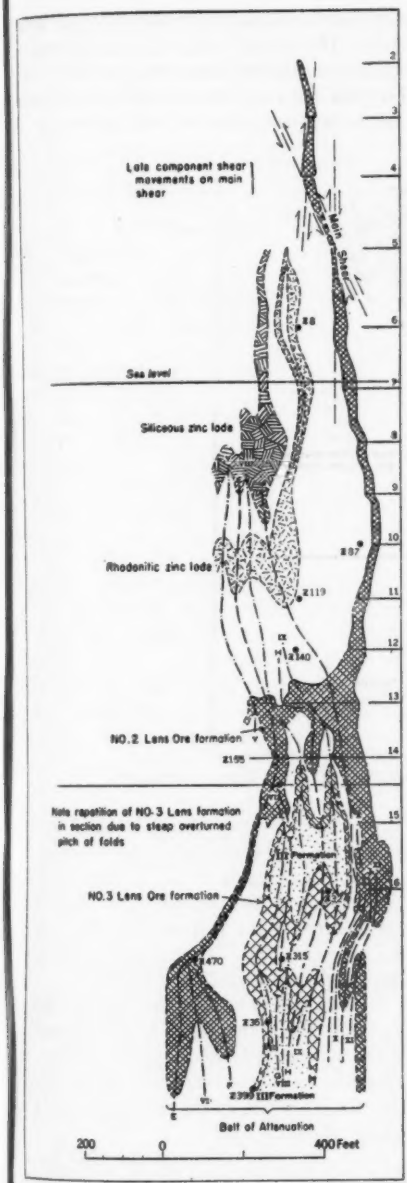


FIGURE 29.—ZINC CORPORATION, SECTION 24 SHOWING LOCAL SEVERE CHANGE IN PITCH

with strong faults of the first group warping them slightly, or they may offset smaller faults of the first group. Movement: East side has moved north and up. Horizontal offset on De Bavay fault approximately half a mile.

(3) Faults with strike approximating N25W to N45W; dip, 55° to vertical NE. Examples: Numerous small unnamed faults cutting across the Potosi-Footwall gneiss of the Footwall basin. Characteristics: Sharp fractures or zones of shear 1 inch to 10 feet wide, frequently containing pegmatite dikes. The uralite dolerite dikes have a similar strike and may occupy faults of this group. These dikes appear to have been offset by small faults of the first group. Movement: East side has moved north; vertical component unknown but probably in most instances east side is the downthrow side. Maximum horizontal offset mapped, about 300 feet.

There are other miscellaneous small faults less easily classified. The Consols vein, for example, occupies a fault of small offset striking NW and dipping flatly SW.

The British fault and De Bavay fault, which alone have an important bearing on the immediate problems, are discussed in detail.

British fault.—The British fault causes a major interruption in the continuity of ore bodies between the Thompson Shaft section of the British Mine and the Junction Mine. Where the southern part of the fault crosses the Hanging Wall granite and Town amphibolites on the rim of the Broken Hill basin, where it crosses the Consols amphibolites in the Alma antcline, and to a less certain degree where it crosses the Potosi-Footwall gneiss in the Footwall basin, the rocks appear to be sharply ruptured and offset by a narrow well-defined fault plane. North and west of here, however, in the region of the lodes, the rocks have been dragged and sheared into their new position across a zone of warp extending several hundred feet on either side of the fault plane. The amount of movement in this warped zone is very important in determining whether the ore-bearing folds in the British Mine are the same as the ore-bearing folds in the Junction Mine. The ore bodies of both mines unquestionably belong to the No. 2 and No. 3 Lens ore formations.

The direction of movement is obvious. The Junction side has been thrown north (west on mine co-ordinates) with respect to the British side. The Junction side has also moved up with respect to the British side (a condition revealed

by the repetition of the underwall of the Footwall-Potosi gneiss in the Footwall basin. The magnitude of the fault movement cannot be measured directly and must be estimated from circumstantial evidence.

movement as is required by the striations noted above. The reappearance of the underwall of the Potosi-Footwall gneiss at the surface in the Footwall basin is further evidence of a substantial vertical component of fault movement.

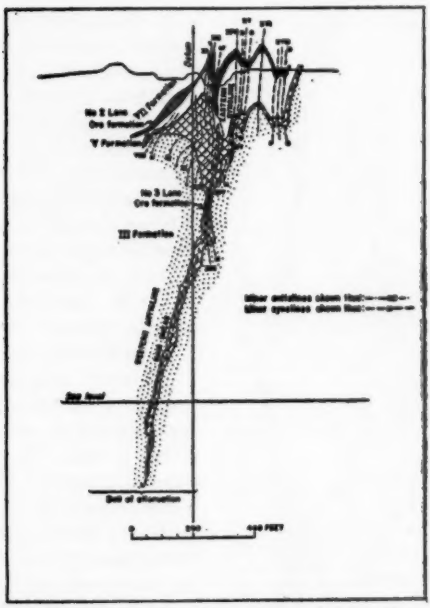


FIGURE 30.—B.H.P. SECTION 41, SHOWING THE MAIN SHEAR SYNCLINE

That evidence is in the form of facts suggesting that the Junction (-Junction North-North Mine) ore-bearing folds are the same as the ore-bearing folds in the Thompson section of the British Mine. Obviously, if the ore-bearing folds in the Junction Mine are *not* the same as those in the British Mine, the Junction folds must be a more easterly group. The evidence that the ore-bearing folds on both sides of the fault are the same is chiefly as follows:

(1) The amount and direction of fault movement necessary to explain the offset in the ore bodies is consistent with observed horizontal components of fault offset and also with fault striations which were observed to pitch 67° southeast in the plane of the fault on the surface in M. L. 285. On the other hand, according to the hypothesis that the Junction ore bodies occupy more easterly folds, the British fault can have no appreciable vertical component of

(2) The fault movement required for offsetting the ore-bearing folds also is suitable to explain the dragging of No. 3 Lens synclines "P", "Q", and "R" into anticlinal shapes that has occurred in the British Mine just south of the fault (Fig. 28). (This dragging may, however, be due to second-order folding).

(3) The lack of any outcrops of south-pitching folds south of the British fault corresponding to the more easterly folds hypothecated for the Junction ore bodies supports the contention that the ore bodies on the two sides of the fault occupy the same folds.

(4) If the belt of attenuation has jumped from one set of folds to another set at the British fault, it might be reasoned that the belt of attenuation and the British fault were both superimposed on the earlier folds at the same time in response to the same stresses; but all other evidence suggests that the belt of

attentuation was developed during folding (by plastic deformation) and that the British fault was developed much later. The crossing of the line of lode by the British fault at the exact place where the belt of attenuation jumps from one set of folds to another must be pure coincidence then, unless there are two belts of attenuation—one strong to the south of the fault, the other strong to the north of the fault. Neither explanation is as satisfactory as our explanation that the ore bodies occupy the same belt of attenuation in the same folds on both sides of the fault.

(5) Occupation of the same folds by the ore on two sides of the fault requires a simpler, more easily understood picture of a single governing ore structure.

(6) Small dragfolds and minor folds in the British and Junction Mines near the fault tend to substantiate the structure required by the hypothesis of a single group of ore-bearing folds offset by the fault.

(7) Folds in XII Formation corresponding to the ore-bearing folds are evident in the North Mine. There is no evidence of an additional more westerly set of folds in XII Formation such as would be expected if the British ore-bearing folds are more westerly than those of the North Mine.

Correlations of structures across the fault were made according to their shape and proximity to the upward expending plastically sheared east limb of ore. The fault movement obtained by comparing correlated axial line points on both sides of the fault by descriptive geometry gave values as follows (assumed dip 65° 46′):

Fault properties measured	Axial Line Points				
	WAO3	ESO3	WAU3	ESU3	RO3 & ro3
Vertical displacement	2032′	1936′	1158′	1019′	2118′
Horizontal displacement	985′	980′	1085′	1149′	1085′
Slip (movement in plane of fault)	2260′	2170′	1598′	1537′	2380′
Offset in 400 scale longitudinal projection	325′S	301′S	320′N	420′	338′
Horizontal offset measured along strike of fault	820′	827′	1190′	1250′	1065–900′
Plunge (true vertical angle)	64½°	63°	47½°	42°	62¼°
Azimuth of plunge	S69E	S67E	S33E	S27E	S67E
Pitch (angle in plane of fault	79°	77½°	52°	46½°	78°
Ratio: $\frac{\text{vertical displacement}}{\text{horizontal Displmt.}}$	2.48	2.34	.98	.82	1.95

There is a fairly wide range of values obtainable depending not so much upon the correlation of structure as upon the assumptions made in projecting structures to the fault plane through the warped zones immediately adjacent to the fault.

Other important properties of the fault are:
Strike Average N4W (magnetic)
Dip: Variable to the east; averages about 65° 46′ according to a contour study of underground information available for about 800 feet below the surface; measured at 81° on the surface in M. L. 285.

De Bavay fault.–The De Bavay fault is approximately parallel to the British fault in strike and probably also in dip. The direction of horizontal offset is the same for both faults, but the magnitude of offset differs considerably. Whereas the horizontal component of movement on the British fault is between 500 and 1250 feet, it appears to be about 2000 feet on the De Bavay fault. It is safe to infer that the vertical component of movement is the same in direction but greater in magnitude on the De Bavay fault. The British fault is marked either by a very narrow schisted zone or by a broader zone of warp. The De Bavay fault is marked by a crush zone of mica schist 200 feet wide.

The ore bodies of the North Mine unquestionably terminate where they meet the De Bavay fault. Vital geological problems are consequently (a) the "behavior" of the ore bodies between present workings and the fault, and (b) the possibility of ore repetitions beyond the fault. The first problem is not considered in this paper. The second problem, involving interpretation of the very complex rock structures beyond the fault and estimation of the fault movement, is investigated in some detail under "Geology from De Bavay Fault to Round Hill". Only the conclusions are stated here. The structure is too complex and the evidence too meagre to permit a definite quantitative conclusion.

The strike of the De Bavay fault is N15W (magnetic). The dip is steep to the east, probably about 60°. The steeper dip agrees with most surface measurements, but many surface measurements, but many surface measurements of the dip of the British fault gave readings of around 80°, whereas contouring of more accurate underground data suggested an average dip of around 66°.

The amount of fault movement is conjectural, only the horizontal component being known with any precision. However, a vertical component of movement around 2300 to 2500 feet appears to fit in best with our structural data and interpretations. Such a movement gives a ratio of vertical displacement to horizontal displacement comparable to that measured for the British Fault. Such a movement also obviously would lift up the ore-bearing North Mine folds on the far side of the fault.

Buckles

General discussion.—The term "buckles" is used in this report to distinguish certain steeply pitching contortions which are clearly younger than the folds which they deform. They apparently belong to the second main period of deformation to which also belong the major faults.

The main shear has already been described as a plastic shear or stretch zone. Only locally does this structure look like a shear. We believe that it resembles a shear only where it has served as a locus of appreciable movement during faulting.[20] Other lesser shears have a similar origin. Numerous small drag folds in the main shear pitch very steeply north or south (See "Mechanics of Folding"). They indicate movement on the shear in response to an essentially horizontal stress couple, whereas the essentially flat-pitching "folds" are referable to a nearly vertical stress couple. Almost invariably the drag folds on the shears indicate that the west side has moved north with respect to the east side (a direction of movement that is the same as that of the Globe-Vauxhall crush zone which is roughly parallel to the main shear).

Furthermore, ore shoots within the main shear lode itself generally have nearly vertical axes in contrast to the flatter pitch of ore occupying folded rock layers. Figures 31, 32, and 33 illustrate this condition in the southern part of the field. Widths of workings in "shear ore" were plotted in longitudinal section and the widths contoured. Bulges on the main shear are seen to pitch steeply. The bulges are believed to have been formed by drag-folding of the shear itself. The deep ore won by the Central Mine is a notable example. Figure 34 illustrates the probable mechanism of drag-folding.

Steeply dipping transverse belts in which folds change their pitch have already been mentioned in the section on "Mechanics of Folding". One of the best illustrations of reversal of pitch occurs in the Central Mine vertically above the deep ore described above. The reversal is attended by a marked warping of the axial plane of the western anticline, but because of a strong second-order fold, it is difficult to determine how much of warping of the axial lines (and changing of pitch) can be attributed to buckling and how much to folding.

In numerous other places there appears to be puckering of the folds west of the shear with comparatively little modification of the shear zone and virtually no modification of the rocks east of the main shear. Possibly, movements resulting from bending of the hanging wall rocks were dissipated on the shear. Certainly the footwall rocks seem to be very little affected.

[20] Schisted zones in this district all appear to have been formed by faulting, not by the plastic "shearing" or stretching of folding. Some local movement on the main shear may also be post-lode in age.

A transverse buckle of major importance occurs in the vicinity of Howell Shaft on the British Mine where no shear comparable to the

Not all of the buckles are referable to the Globe-Vauxhall direction of shearing. The rocks (and ore bodies) in the North Mine encounter

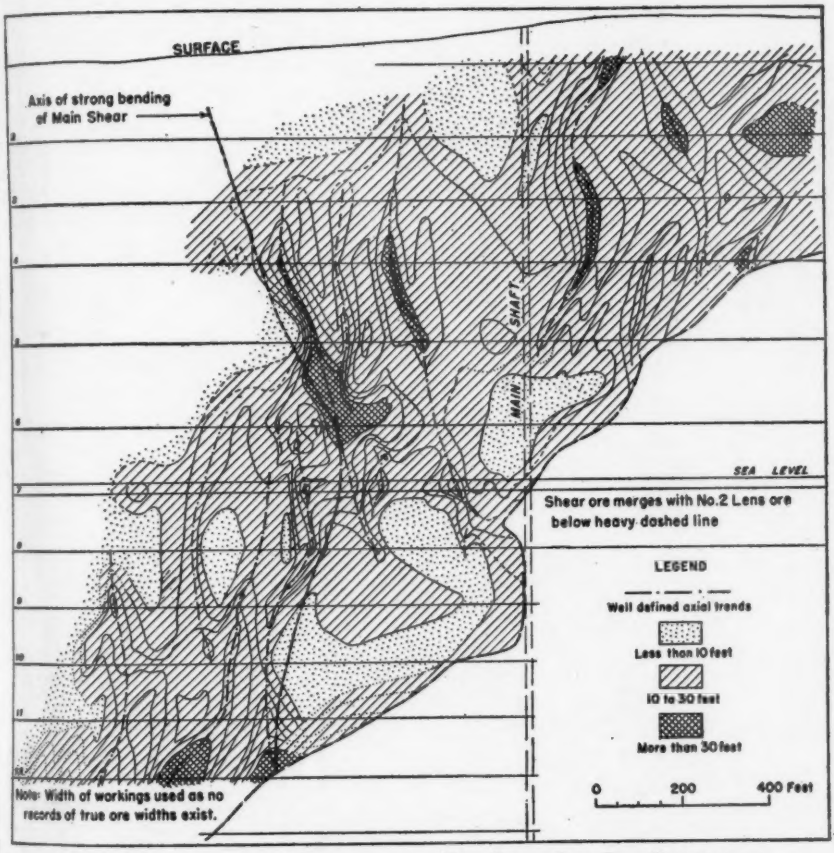

SURFACE
Axis of strong bending of Main Shear
SHAFT
MAIN
SEA LEVEL
Shear ore merges with No.2 Lens ore below heavy dashed line
LEGEND
Well defined axial trends
Less than 10 feet
10 to 30 feet
More than 30 feet
0 200 400 Feet
Note: Width of workings used as no records of true ore widths exist.

FIGURE 31.—LONGITUDINAL PROJECTION OF MAIN SHEAR ORE, ZINC CORPORATION

main shear exists. Its axial plane is steep. The buckle is responsible for a change of pitch in the folds here. Its proximity to the British fault strongly suggests a genetic relationship, although the resolution of stresses is by no means clear. The structure is further complicated here because movement, presumably on the British fault, has drag-folded the minor folds of where they emerge from the buckle. The resulting double folds in this instance so closely resemble second-order folds produced during the folding period that their origin is somewhat doubtful.

steep north-pitching buckle in about section 27 that was clearly caused by drag in sympathy with the De Bavay shear movement. It is the first of a series of such buckles between here and the De Bavay Fault.

In the South Mine there appears to be some correlation between a steeply inclined belt of north-pitching structures, steep axes of bulge ore on the main shear, and marked bends in the shear itself. Here the buckles appear to be the "hinges" on which the main shear changes its

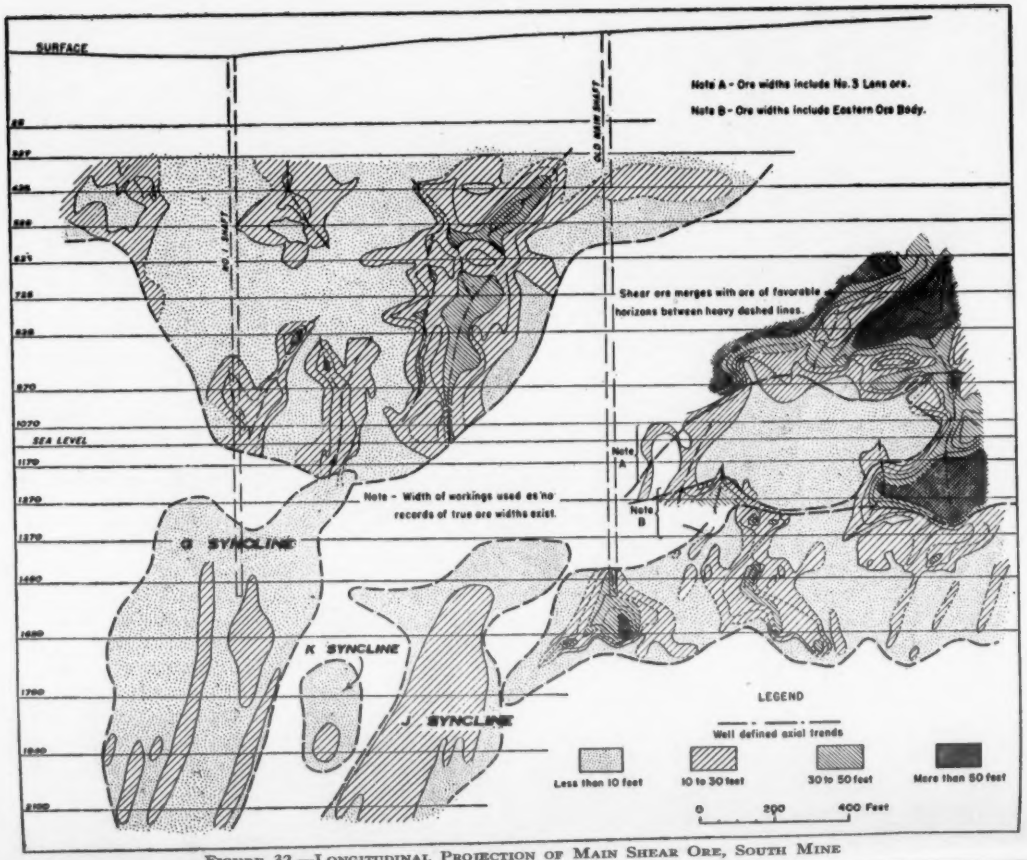


FIGURE 32.—LONGITUDINAL PROJECTION OF MAIN SHEAR ORE, SOUTH MINE

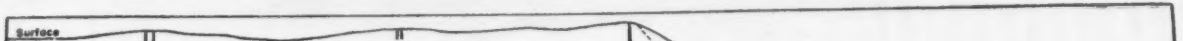


FIGURE 32.—LONGITUDINAL PROJECTION OF MAIN SHEAR ORE, SOUTH MINE

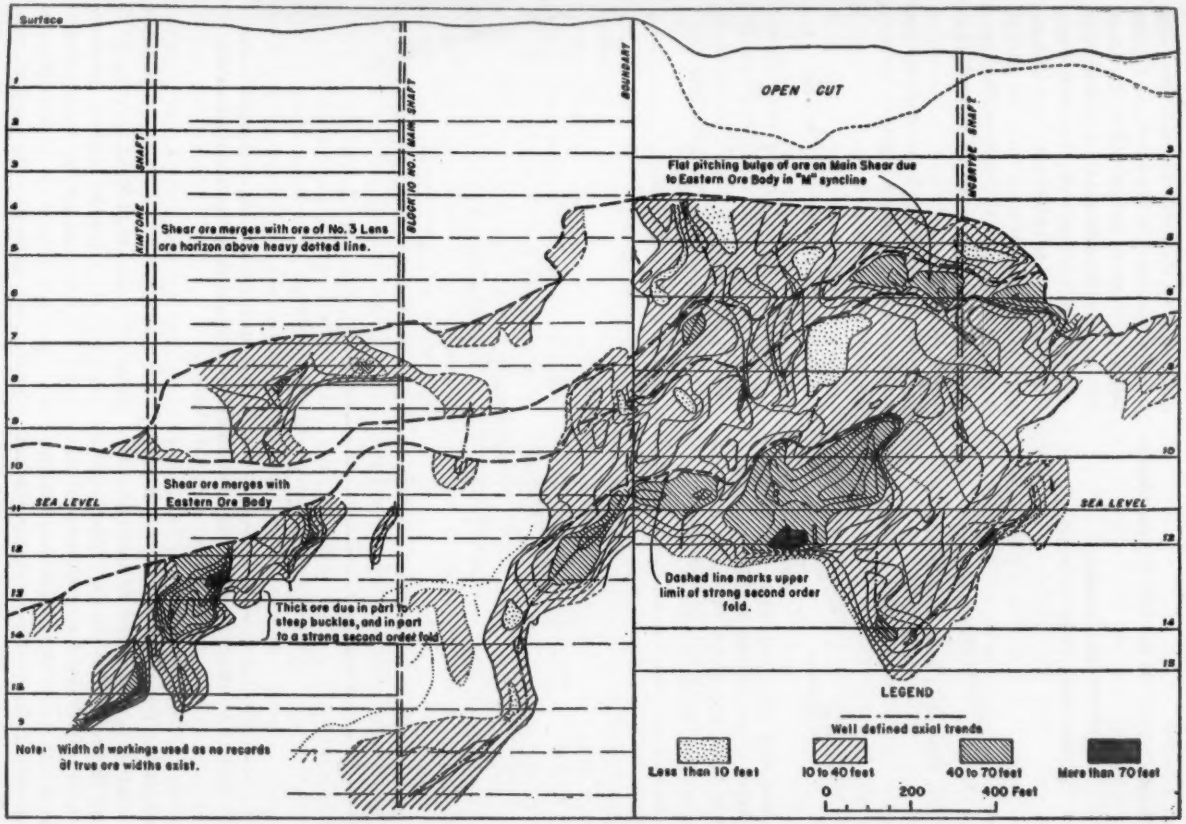

Surface
KINTORE SHAFT
BLOCK 10 NO. 1 MAIN SHAFT
BOUNDARY
OPEN CUT
WEBSTER SHAFT
Flat pitching bulge of ore on Main Shear due to Eastern Ore Body in "M" syncline
Shear ore merges with ore of No. 3 Lens ore horizon above heavy dotted line.
Shear ore merges with Eastern Ore Body
SEA LEVEL
SEA LEVEL
Thick ore due in part to steep buckles, and in part to a strong second order fold
Dashed line marks upper limit of strong second order fold.
Note: Width of workings used as no records of true ore widths exist.
LEGEND
Well defined axial trends
Less than 10 feet
10 to 40 feet
40 to 70 feet
More than 70 feet
0
200
400 Feet

FIGURE 33.—LONGITUDINAL PROJECTION OF MAIN SHEAR ORE, BLOCK 10 AND B.H.P. MINES

strike. The relationship is general rather than exact, however.

The main shear on the Zinc Corporation as

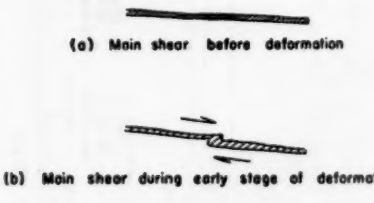

(a) Main shear before deformation
(b) Main shear during early stage of deformation
(c) Main shear following deformation and mineralization
bulges of ore pitch very steeply south

FIGURE 34.—DEFORMATION OF THE MAIN SHEAR BY PORT FOLDING MOVEMENTS

Economic significance.—The chief economic significance of the buckles is that they control in large measure the ore shoots in the steep tabular portions of the lode (Figs. 31, 32, and 33). In the south drives of the Zinc Corporation where the lode becomes very narrow it is sometimes difficult to tell whether the end of payable ore has been reached or whether more southerly bulges can be expected. Similar difficulties are being encountered on the lower levels of the South Mine.

Recognition of buckles is also important when making projections of ore structures to (newer) deeper levels.

Small Faults Affecting the Lodes

Faulting before and during mineralization.—Numerous small faults of different ages have affected the ore-bearing folds. Fault movements of small magnitude on the main shear and on

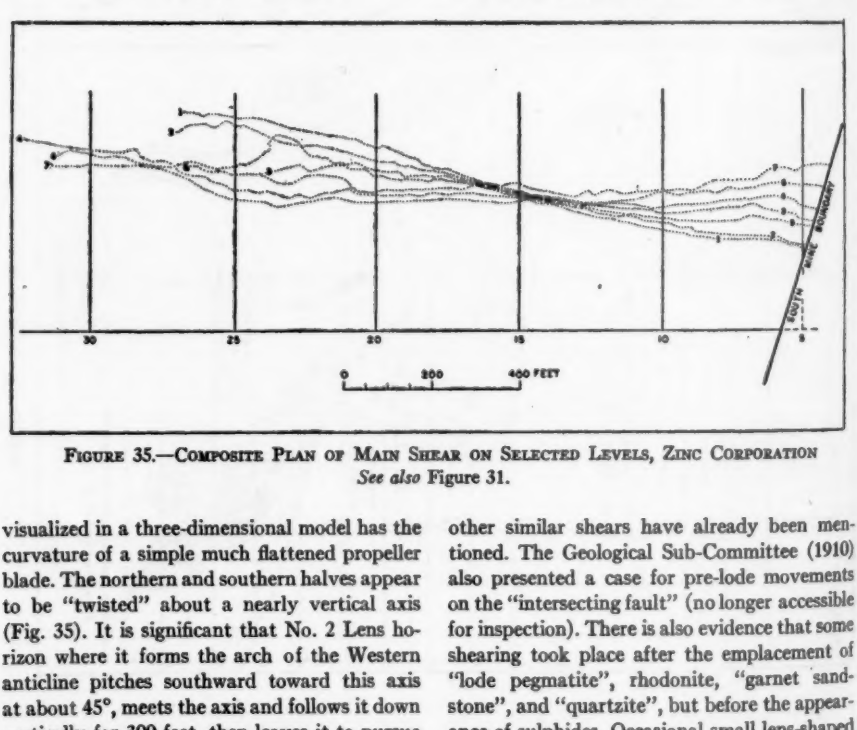


FIGURE 35.—COMPOSITE PLAN OF MAIN SHEAR ON SELECTED LEVELS, ZINC CORPORATION
See also Figure 31.

visualized in a three-dimensional model has the curvature of a simple much flattened propeller blade. The northern and southern halves appear to be "twisted" about a nearly vertical axis (Fig. 35). It is significant that No. 2 Lens horizon where it forms the arch of the Western anticline pitches southward toward this axis at about 45°, meets the axis and follows it down vertically for 300 feet, then leaves it to pursue a more normal course of about 35°. No. 3 Lens ore formation is but little affected.

other similar shears have already been mentioned. The Geological Sub-Committee (1910) also presented a case for pre-lode movements on the "intersecting fault" (no longer accessible for inspection). There is also evidence that some shearing took place after the emplacement of "lode pegmatite", rhodonite, "garnet sandstone", and "quartzite", but before the appearance of sulphides. Occasional small lens-shaped bodies of rhodonite, "garnet sandstone", or "quartzite" occur with bedding planes of en-

closing (sheared) gneiss wrapping around them. Some of these lenses were once connected as a continuous rock layer first stiffened and made brittle by replacement (or by metamorphism. See earlier discussion of lode mineralogy) and then pulled apart by shearing stresses. The lenses are sometimes veined by later quartz and sulphides and by small quartz-biotite intergrowths. Large masses of rhodonite in No. 3 Lens ore formation were also fractured before the appearance of later minerals, as is evident in the Block 14 and British Mines.

The main shear, moreover, frequently bends at both the overwall and underwall of the "broad lodes" as if the favorable formations either before or after lode formation acted as a fulcrum. (For example, the "propeller blade" shape of the main shear in the Zinc Corporation.) The sulphides are not deformed. Possibly the bending occurred after the early gangue minerals formed but before the sulphides appeared, although either late folding movements or pre-lode faulting might be responsible for such bending.

Post-ore faulting.—Countless post-ore faults and joints both flat and steep cut the ore bodies. The displacement on these is negligible. Some of the larger ones are large open cavities several feet across where encountered in stopes. The walls of the cavities are lined with secondary minerals. Other faults are tight cracks containing only thin films of secondary minerals. Still others contain pug seams up to 1 foot wide.[21] Because these faults had no bearing on the immediate problems of the Central Geological Survey they were not studied. Nevertheless, they are responsible for most of the bad ground along the line of lode, which causes the heavy falls of ground and resulting loss of life and loss of dividends.

Many of the post-ore faults originated prior to ore emplacement but were reopened later. One prominent fault of this kind in the North mine inhibited mineralization, strong ore stopping against silicified selvedge on both sides of the fault.

[21] There is some evidence that pre-ore faults of the main faulting period converted the rock to schist, whereas post-ore faults, probably formed under lighter load, converted the rock to fault gouge or pug.

Drag Folds with Flat South Pitch

Small drag folds with flat south pitch characteristically about 36° are abundant in the Junction, Junction North, and North Mines (i.e. north of the British fault) although major folds and ore bodies pitch north. They were very misleading until it was recognized that they constitute a new structural "texture" superimposed upon and but very slightly modifying the original folded pattern, and represent a post-folding period of movement as yet not fully understood but manifestly pre-ore in age. This type can often be distinguished from drag folds of the main folding period in the following manner:

(1) Regardless of the strike and dip of bedding planes, practically 90 per cent (or more) of the crinkles show that the east side has moved up with respect to the west side.

(2) Often the crinkles appear to be aligned along a fracture.

(3) Crinkles of this type characteristically fail to show appreciable thickening of beds on the crests and troughs with consequent thinning on the limbs as do drag folds of the main folding period.

Mechanical Interpretation of Faulting and Buckling

Materials tested under compression in the laboratory commonly fail along two well defined shear directions with or without the development of a third direction of tension. The two major fault directions (Globe-Vauxhall and De Bavay) possibly may be regarded as these two shear directions. The buckles and small drag-folds on the main shear then appear as manifestations of the Globe-Vauxhall direction of shearing where a dragging movement embracing a wider belt of rock has partly or completely taken the place of movement on two sides of a clean break. Thus the buckle in the British mine does not show drag in the right direction to satisfy the British fault movement because it is an expression of the complementary (Globe-Vauxhall) shear direction.

The subsidiary third group of small N25W to N45W pre-ore faults previously discussed, possibly including the fractures occupied by the

small dolerite dikes and occasional pegmatites, may be expressions of the tension direction. Continued movement on the British and De Bavay faults would probably induce such move-

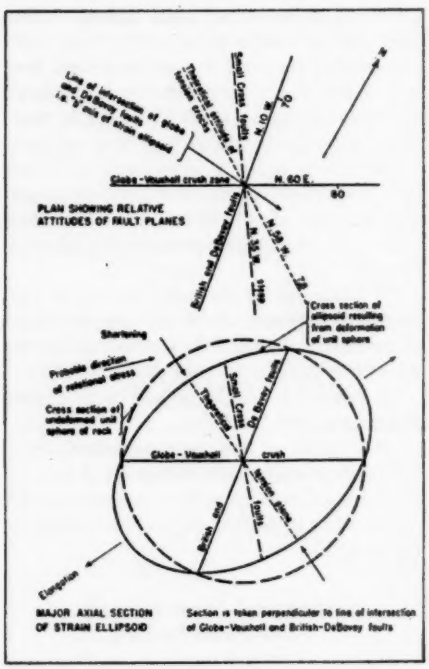

Globe - Vauhall crush zone
N. 60 E.
80
PLAN SHOWING RELATIVE ATTITUDES OF FAULT PLANES
Cross section of ellipsoid resulting from deformation of unit sphere
Shortening
Probable direction of maximum stress
Cross section of undeformed unit sphere of rock
Globe - Vauhall
crush
Elongation
MAJOR AXIAL SECTION OF STRAIN ELLIPSOID
Section is taken perpendicular to line of intersection of Globe-Vauhall and British-DeBavay faults

FIGURE 36.—DIAGRAM SHOWING PROBABLE ORIENTATION OF STRAIN ELLIPSOID IN RELATION TO PROMINENT SHEAR DIRECTIONS

ment on any tension cracks already formed. Movement of this kind on tension breaks with accompanying drag may explain the buckles affecting the North Mine ore bodies between present workings and the De Bavay Fault.

Figure 36 illustrates the pattern of stress and strain relationship in terms of the strain ellipsoid.

Special Structural Studies

Several attempts were made to find a quantitative expression for various structural relationships that we knew only in a qualitative way. The results were not significant enough to warrant more than mention here.

Structure contours of the main shear.—The main shear, where recognized as a structural element in the Zinc Corporation, South Mine, Central Mine and B. H. P. Mine, was analyzed in a three-dimensional way by the method of structure contours, based on the technique developed by Connolly (1936). A theoretical plane whose strike and dip were the average strike and dip of the main shear was first determined. The horizontal distances which separated this plane from the main shear were measured and the figures representing these distances plotted in longitudinal section and then contoured. The resulting plan shows the "topography" of the footwall of the main shear. The longitudinal section compared with longitudinal sections showing such features as pitch of ore bodies, widths of main shear ore (i.e. buckles) and grade-width distribution revealed poor relationships, but none warranted further analysis. Garretty subsequently applied the method successfully to predict pitch changes in the North mine.

Statistical strike—dip—plunge[22] *relationships.*—A highly important characteristic of the line of lode is that changes of pitch in the ore bodies are accompanied by changes of strike. Just as the lode describes a broad arc in longitudinal section with north pitch at the north end and south pitch at the south end, so does it describe an arc in plan. Even small wobbles in the pitch lines are almost invariably accompanied by wobbles in the strike. A quantitative expression for this relationship would be valuable in exploration of northern or southern extensions of the line of lode, since strikes can be determined fairly reliably in overlying rock but continuous accurate pitch data are impossible to get.

The main shear, the only measurable structural element available, was analyzed for strike and dip[23]. Axial line points were taken on immediately adjacent folds and the plunge calculated in each instance. A common reference strike line was determined and all strike measurements were converted into positive or

[22] Plunge is the true vertical angle between two points on the same structure, whereas pitch is the angle measured in the plane of the structure. (In the case of folds, pitch is measured in the axial plane.)

[23] This work was done before the strikes of axial planes were determined. But the strikes of axial planes are inferred and therefore cannot yield accurate measurements.

negative departures from this reference strike. The horizontal was taken as the reference for the dip and plunge. Corrected strike, dip, and plunge values for each of 150 places were written on separate cards, and the data were then analyzed according to standard statistical practice for correlation. Constants derived were:

Quantities Correlated in Pairs	Statistical indices					
	(r)	(P.E.r)	(η)	(η^2-r^2)	σ	3
Strike-Dip	0.0898	—	0.241	—	—	—
Strike-Plunge	0.4730	0.0428	0.607	0.1441	0.062	0.186
Plunge-Dip	0.420	—	0.384	—	—	—

r = Correlation coefficient
P.E.r = Probable error of the correlation coefficient
η = Correlation ratio
σ = Standard deviation

There was a fair correlation between strike and plunge and a negligible correlation between strike and dip and between plunge and dip. There is, moreover, no valid evidence of non-linearity in the relationship between strike and plunge.

A formula was developed by the method of least squares expressing the (linear) relationship between strike, dip, and plunge:

Plunge = 0.858 strike + 0.305 hade − 2,

where south pitch is taken as positive and north pitch as negative; where strike is given as positive (clockwise) and negative (anti-clockwise) from a datum whose bearing is 55° 44′ magnetic and whose dip is expressed as the positive (west) and negative (east) hade of the shear.

The formula, however, does not accurately express the relationship in any individual case and is therefore of very limited practical use.

(As might be expected in cases of plastic folding, the relationships between dip, strike, and pitch are wholly unlike the theoretical relationships that should obtain if the rocks were simply bent.)

Region from De Bavay Fault to Round Hill

General statement.—Such structural features as the Footwall basin, Alma anticline, and eastern leg of the Hanging Wall basin can be recognized without difficulty in their offset positions beyond the De Bavay fault (Pl. 1). Determining the precise faulted position of the North Mine ore-bearing folds is not so simple, as it involves interpreting a region of great structural complexity with too scanty evidence. Several alternative interpretations are possible.

Stratigraphy east[24] *of De Bavay fault.*—The coarse garnet gneiss forming the core of the Eastern anticline is the same on both sides of the fault and consists almost certainly of I and III Formations. The lowermost lode horizon lying above the coarse garnet gneiss and traceable from the De Bavay fault along the east (south) side of Imperial Ridge and Round Hill to the Globe-Vauxhall crush zone is very probably No. 3 Lens ore formation. The Hanging Wall granite can also be recognized with certainty wherever mapped, and there is no doubt concerning the presence of the Potosi-Footwall gneiss in M. L. 3 (although a small portion of the quartzite shown as underlying the Potosi-Footwall gneiss closely resembles that formation also).

There is greater doubt as to the exact stratigraphic position of other rocks. "Difficulties" inherent in any interpretation are that (a) The Potosi-Footwall gneiss formation is missing between the No. 3 Lens ore formation and the Hanging wall granite, and in fact outcrops only in M. L. 3[25]. This formation is, however, also missing in the west limb of the Western anticline for considerable distances along the line of lode. Also, whereas only two thin amphibolites intervene between the No. 3 Lens ore formation and the Hanging wall granite in M. L.

[24] For east read north if thinking in terms of North Mine co-ordinates.

[25] Between the uppermost and next lower amphobolite in the Imperial Ridge syncline is a coarse granular rock which closely resembles Footwall gneiss in some instances, but in other instances appears to grade into amphibolite. We believe that it is sedimentary material which suffered contact metamorphism at the time of amphibolite intrusion.

44, at least four amphibolites, including one very thick one, intervene between these two formations in the Imperial Ridge syncline. (The big amphibolite mass at Round Hill possibly marks a center of intrusion.) Thickening in the troughs and thinning on the limbs in evidence everywhere may account for the apparent discrepancy even if original lenticularity is not considered to be a contributing factor.

Structures east of De Bavay fault.—Several prominent structures require explanation and correlation.

The double anticline of Potosi-Footwall gneiss in M. L. 3 looks like a fold rather than a buckle because of the great thickening and thinning of material in different parts of the structure, the profuse development of minor folds, and its flat pitch. The dragfolds suggest, but do not prove, that the fold is a first-order fold rather than a second-order fold. The syncline of Hanging wall granite in the corner of M. L. 44 resembles a buckle rather than a true synclinal fold, with angular dragfolds without noticeably thickened noses, nearly vertical pitch, and incipient schisting of the rock. Compare the amphibolites here with the Consols amphibolites wrapping around the northeast end of the Footwall basin. The Imperial Ridge syncline is a tightly folded syncline with predominant flattish south pitch except at its south end where the reversal of pitch is extremely abrupt and was apparently assisted by faulting. The Round Hill syncline is a similar, though smaller, structure. The Imperial anticline is a very tight attenuated structure. The amphibolites of the Imperial Ridge syncline should underlie the Hanging wall granite in the Hanging wall basin, but they are missing along the west limb of the Imperial anticline. Their elimination probably occurred during folding, although there may have been some later faulting here.

Various faults other than the De Bavay fault occur; the most important is the Imperial Dam fault whose exact strike, dip, and movement are unknown.

Alternative structural interpretations.—Continuity of these structures is broken at both the De Bavay and Imperial Dam faults. The three following structural interpretations indicate the range of uncertainty in correlating the various folds across these two faults. Minor modifications of these interpretations are also possible.

INTERPRETATION NO. 1: This interpretation, which is portrayed on the surface plan and cross-sections is preferred. (See Fig. 37). The essential thing to note is that the westernmost of the two anticlines in M. L. 3 and one minor anticline belonging to the Imperial Ridge anticline are both considered to be the Western anticline which contains the North Mine ore bodies. On this hypothesis, exploration for the No. 2 Lens and No. 3 Lens ore formations within these structures east of the fault *might* find ore[20]. Even if these structures are not the the same as the North Mine ore-bearing fold, they are very similar structures worth exploring.

According to this interpretation, the "syncline" of Hanging wall granite and Town amphibolites in the northeast corner of M. L. 44 is regarded as a buckle, as the field evidence suggests, rather than a normal fold.

The Imperial Ridge syncline, Round Hill anticline, and Round Hill syncline must be regarded as folds on the west flank of the Eastern anticline which die out southward. By a combination of pitch changes and fault movements, the Imperial Ridge syncline must be sufficiently high above the surface south-west of the De Bavay Fault to prevent the occurrence of outcrops of No. 3 Lens ore formation on that side of the fault. An abrupt pitch change and considerable vertical throw on the Imperial Dam fault are necessary postulates. The great thickness of Town amphibolites in the structure suggests that the sills were possibly originally abnormally thick at this place before folding.

INTERPRETATION NO. 2: This interpretation (Fig. 37) (a) supposes rather drastic changes in the fold in a short distance (wherein fold No. 3 takes the place of fold No. 1 as the main

[20] Even if this correlation is absolutely correct, there is no guarantee that the favorable beds would be ore-bearing in these structures. The faulting occurred before mineralization, and the ore solutions may have had sufficient access to the structures on only one side of the fault. There was also a tendency for ore deposition to be poor immediately to the north of strong tranverse structures—e.g. just north of the strong buckle in the Central Mine, north of The British fault in the Junction Mine, and north of the buckle in Section 27 in the North Mine.

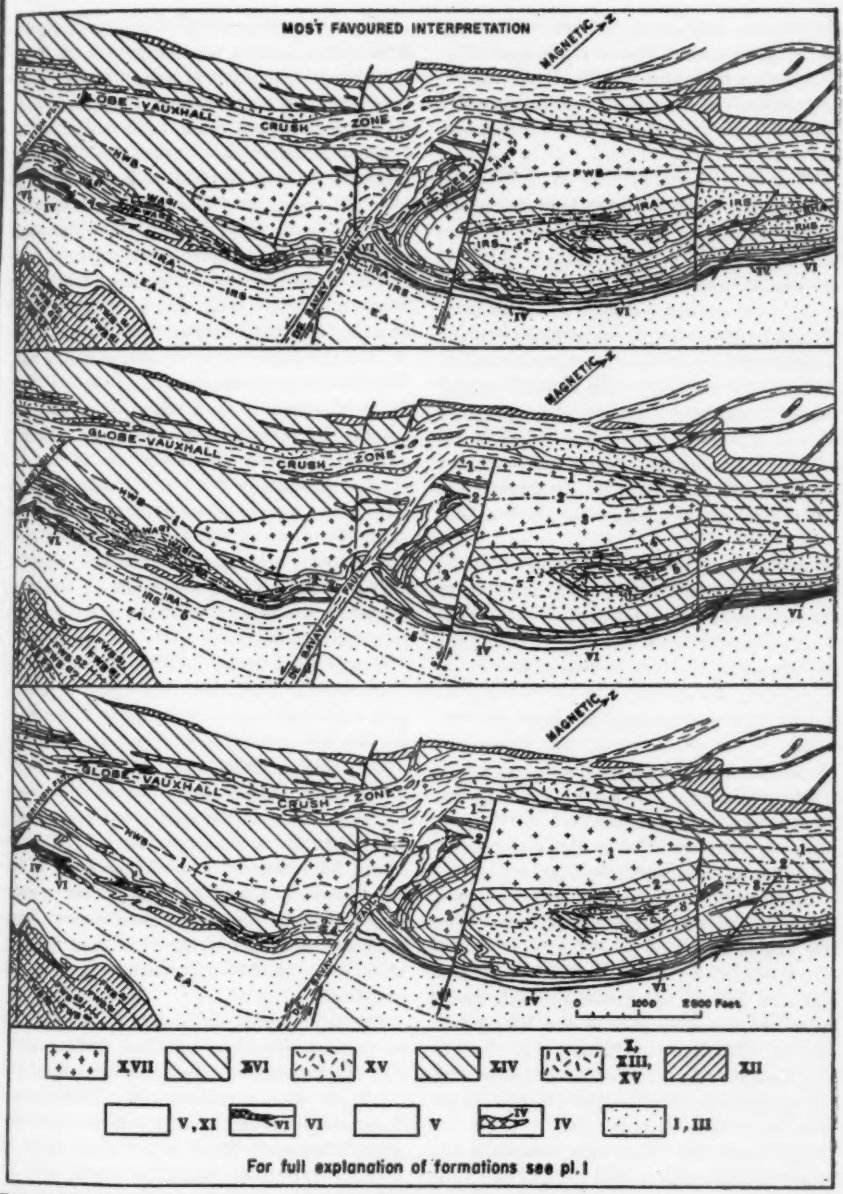


FIGURE 37.—SKETCH PLANS INDICATING THREE POSSIBLE INTERPRETATIONS OF GEOLOGY FROM THE DE BAVAY FAULT TO ROUND HILL

structure of the Hanging wall basin in a very short distance), and (b) requires apparently inconsistent offsets on the Imperial Dam fault. The possibilities of ore repetitions remain essentially as they were under interpretation No. 1.

INTERPRETATION NO. 3: The same objections can be raised against this interpretation (Fig. 37) as against interpretation No. 2. The exploratory objectives, however, remain virtually unaltered.

Region from Zinc Corporation to White Lead

General description.—The region between the Hanging wall basin and the Broken Hill basin was mapped for 3½ miles south of the Zinc Corporation boundary. Outcrops are sparse here, and the geology was difficult to interpret, although magnetic surveys determined in many places the position of the garnet-magnetite bed which occurs just below the Potosi-Footwall gneiss. Subsequent correlation of the geophysical and geological data has resulted in the geological interpretation worked out jointly by King and Gustafson in 1947, modifying The Central Geological Survey interpretation (Gustafson, 1939).

The interpretation is probably substantially correct in its broad outlines, but built on scanty data it is inevitably inaccurate in detail. The garnet-magnetite bed is lenticular; and in some instances where it as well as mappable contacts are missing, the geology had to be projected for long distances. As an example of the kind of uncertainty which exists, the Rising Sun anticline is unquestionably the equivalent of Western anticline as indicated on the map, but it is uncertain whether WA^{a1} or WA^{a2} is the dominant minor anticline in this major structure. Also the southern continuation of WA^{a1} is considerably in doubt. The pitch of most structures had to be inferred indirectly from other evidence.

On the positive side, the finding of a garnet-magnetite bed at the Potosi-Footwall gneiss contact in the east limb of the Rising Sun anticline (Western anticline) goes far to strengthen the correlation of Potosi gneiss with Footwall gneiss upon which the structural interpretations in this report is based.

Major structures.—The major structures recognized in this area are from west to east: The Hanging wall basin, Rising Sun anticline (equivalent of Western anticline), Footwall basin, Alma anticline, and Broken Hill basin. Many minor folds have been detected but less than farther north where data are more numerous.

The way in which the Western anticline grew large as the Eastern syncline grew small going southwards in the central part of the field continues in a striking manner approximately as far south as the old White Lead prospect. The Eastern anticline, if it exists at all in this region, is a small dragfold no longer recognizable, but the relative behaviour of the Western anticline (Rising Sun anticline) and the Alma anticline expresses this change of emphasis from eastern to western structures going south. The Western anticline is clearly the dominant anticline between the Hanging Wall basin and the Broken Hill basin in the vicinity of Rising Sun, whereas around the Zinc Corporation New Main (Freeman) shaft the Alma anticline reaches higher than the Western anticline. Note, for example (Pl. 1) how the Alma anticline as defined by the Potosi-Footwall gneiss formation plunges beneath the surface about 9,500 feet south of the Zinc Corporation New Main shaft, whereas the Western anticline (Rising Sun anticline) as defined by the same formation continues above the surface for 7000 feet south of there.

Somewhere near the old White Lead prospect, however, the Alma anticline again begins to play a dominant role, as revealed by the outlines of the Town Amphibolite and the Hanging Wall granite in these two structures. The Western anticline (Rising Sun anticline) as outlined by these formations plunges beneath the surface well ahead of the Alma anticline (Pl. 1). Thus about 3000 feet south of White Lead is the same kind of "axis of twisting" between anticlines (between Rising Sun anticline and Alma anticline) as occurs in the vicinity of Delprat shaft (between Western anticline and Eastern anticline).

(As here interpreted the fold AA^{a1} which constitutes the Alma anticline farther north actually becomes a very small fold south of the Air Shaft, whereas the minor fold FWB^{a3} grows large and takes its place as a major structure going southward. There is thus a choice as to whether this major anticline should still be called the Alma anticline or given a new name.)

Problem of pitch and ore possibilities.—Even if the New Broken Hill Consolidated ore bodies do continue indefinitely southward, they are valuable only so long as they remain at a

mineable depth. Plunging below this depth, however, they might reappear farther south within the mineable zone if crests in the pitch line of the Western anticline exist.

Pitch data here are meager and relatively uncertain. Readings on drafgolds could be made in only about ten scattered places. Generally pitch had to be inferred from the distance separating two limbs of a fold and from the size and position of magnetic anomalies defining the garnet-magnetite beds. Such evidence is circumstantial and, although probably fairly conclusive as regards major trends, not wholly reliable for details.

On present evidence, pitch trends south of the Zinc Corporation New Main shaft are on the average flatly south to beyond the old White Lead prospect. Possibly, pitch crests occur in which the favorable beds are closer to the surface than elsewhere.

Outcrops of XI Formation in the Western anticline contain numerous gahnite-bearing siliceous lodes a few of which have contained small lenses of mineable sulphides at White Lead, Rising Sun, and Rising Sun North. Of little or no commercial interest, they testify to the passage of ore solutions through them and, therefore, possibly also through the more favorable formations which lie below. Details of structure could not be successfully worked out from the attitude of these lodes.

Vertical interval between formations.—A limiting factor in drawing pitch lines in longitudinal projection and in constructing cross-sections from projected data is the vertical interval between two formations in the nose of a fold. Although such intervals range considerably over great distances and in different structures, they are not believed to fluctuate rapidly in the same fold. For example, in the construction of the cross-sections, it was found necessary to have a true interval (i.e. measured perpendicular to pitch) of 1630 feet between the underwall of XII Formation and the overwall of No. 2 Lens ore formation in the Western anticline at the Zinc Corporation and an interval of only 800 feet between the same formations in the same structure at the North Mine. Whatever the reason for this discrepancy, either a difference in packing during folding or sedimentary lenticularity (the zinc lodes are absent at the north end), we arbitrarily decided during the construction of cross-sections south of the Zinc Corporation to keep the interval between XII formation and No. 2 Lens ore formation approximately constant at the interval found suitable at the Zinc Corporation. Similarly, the interval between XV Formation and XII Formation was assumed to remain approximately constant. Nevertheless, the total interval between No. 2 Lens ore formation and XII Formation is controlled within narrow limits by surface outcrops.

The fact that XV Formation amphibolites do not outcrop until some distance south of White Lead is in itself evidence of very flat net pitch between the Zinc Corporation boundary and White Lead.

Summary of Major Folds from White Lead to Round Hill

The major folds of the northern, central, and southern portions of the district are listed and correlated in Table 4.

Viewing the district as a whole (Pl. 1), the major structures have a very predominant flat south pitch. The north pitch of the North Mine ore bodies is a very local feature.

Ore Genesis and the Structural and Stratigraphic Control of Ore Deposition

Ore Solutions

Broken Hill ore bodies are the kind generally associated with ore solutions emanating from granitic magmas (Buddington, 1933). If the ore solutions were thin, moderately dilute, hot liquids whose chief component was water, vast quantities of solution had to flow through the rock to form the ore deposit. The average cross section (corrected for pitch) of the Broken Hill ore deposit reveals something like 5,200 tons per linear foot of ore containing (where unoxidized) roughly 14 per cent Pb. and 14 per cent Zn.

Assuming that the ore solutions contained 2 per cent Pb. and 2 per cent Zn., 121,000 tons of ore solution would have to deposit all of its metal content to produce 1 linear foot of the

main Broken Hill lode. To form the ore body 2½ miles long would require 2,240,000,000 tons of ore solution. Further, assuming the solubility of water in a granite melt to be 4 per cent, an underlying granite batholith containing 5 cubic miles of granite would be required to have yielded this amount of ore solution. The widespread mineralization of the district suggests that the granite mass is much larger.

TABLE 4.—MAJOR FOLDS

	At Rising Sun (South end)	At B.H.P. Mine (Middle)	At Round Hill (North end)
West →	Hanging Wall Basin	Hanging Wall Basin	Hanging Wall Basin
	Rising Sun Anticline	Western Anticline	
		Eastern Syncline	Imperial Anticline
		Small minor folds	
	Small minor folds		Imperial Syncline
		Small Minor Folds	Round Hill Anticline
			Round Hill Syncline
		Eastern Anticline	Eastern Anticline
	Footwall Basin	Footwall Basin	Footwall Basin
← East	Alma Anticline	Alma Anticline	Alma Anticline
	Broken Hill Basin	Broken Hill Basin	Broken Hill Basin

Feeder Channels

The ore solutions obviously moved predominantly in the permeable favorable beds up the pitch[27]. The upward extending fin of the main shear above the "broad lodes" may have been locally the avenue of escape for the ore solutions that had completed their job of mineralization. It is an empirical fact that no known ore along the line of lode occurs more than a few hundred feet east or west of the main shear. Consequently, the belt of attenuation may somewhere be a vertical link between the source of the ore solution and the favorable rock formations, although the latter may indeed have been in direct contact with the source.

The obvious shear zones of the district are not the plastic shears developed during folding but the strong post-folding faults (Globe-Vauxhall, British, and De Bavay). The field evidence is that the favorable beds are apt to be barren where cut by these faults. The only important break in the continuity of the main line of lode in the warped zone of the British fault, is due as much to feebler mineralization as to the thinness of favorable beds.

The intersection of No. 3 Lens ore formation (?) (several miles northeast of Broken Hill in M. L. 216) with the Globe-Vauxhall crush-zone does not contain an ore body; what little ore there was in No. 3 Lens appears to have terminated before the fault was reached. Consequently exploration cannot be directed to the intersections of faults with favorable rocks in the hope of finding favorable ore loci. Plastic shears and belts of attenuation involving favorable rocks must be sought.

The size of the igneous mass which contributed the ore solutions suggests that almost any zone of shearing if deep enough would tap the source of ore. Such masses, however, have irregular surfaces with upward projecting knobs or cupolas in which ore solutions probably gather as the magma cools. It may thus require

[27] In the South Mine, Central Mine, and B.H.P. Company Mine, where the pitch of the folds is predominantly south, the Western anticline goes through a sudden reversal of pitch. In each instance the main arch and western limb of No. 3 Lens ore formation ceases to be ore-bearing (although it is feebly mineralized) where the pitch is to the north and just as abruptly takes up its ore-bearing role again where the pitch reverts to the south. In the North mine, however, the ore occurs in North-pitching-folds.

ZINC CORPORATION LTD. | BROKEN HILL SOUTH LIMITED | SULPHIDE CORP LTD. AND BLOCK 10 | B. H. P. CO. LTD. | WILLYAMA MINING PTY. LTD. (BLOCK 14) | NORTH BROKEN HILL LIMITED

BRITISH | JUNCTION | JUNCTION NORTH

Sloped

ORE CONTINUES SOUTHWARD

LONGITUDINAL PROJECTION OF THE MAIN BROKEN HILL LODE

SHOWING THE DISTRIBUTION OF ORE IN FAVOURABLE ROCK FORMATIONS

400 0 2000 FEET

Shear ore prominent

NO. 2 & NO. 3 Lenses incompletely developed but estimated from projection

Zinc Corporation section 10

EXPLANATION

Ore in zinc lodes

Ore in NO. 2 Lens ore formation

Ore in NO. 3 Lens ore formation

NO. 2 Lens partly eroded, but estimated

NO. 2 Lens completely eroded, but estimated

NO. 3 Lens partly eroded, but estimated

NO. 2 Lens eroded in small part, but probably of no importance

Average Tons / Linear foot for whole line of lode (3200 tons/linear ft)

Zone of the "British Fault"

NO. 2 Lens eroded in part but estimated

NO. 3 Lens partly eroded, but estimated

ORE TONNAGE DISTRIBUTION IN THE BROKEN HILL LODES

(1) a feeder channel that will connect such a cupola with (2) a favorable rock in (3) a favorable temperature-pressure environment to produce any ore body. To get a big one, the feeder channel must tap (or consist of) the favorable beds where (4) they have been bunched up into thick folded masses.

Favorable Beds

This Survey has shown that with small exception all of the ore along the main line of lode occurs in a few closely adjacent sedimentary beds, of which the lower two, No. 3 Lens ore formation and No. 2 Lens ore formation, are overwhelmingly important. Other higher horizons were mineralized, and locally contained ore bodies, but only No. 2 Lens and No. 3 Lens ore formations have been mined under average cost-grade relationships. The zinc lodes at the south end of the field, profitably stoped during high metal prices, promise to be of greater economic importance in the future.

Favorable Structures

A great variety of structures influence the shape and size of the ore bodies. Except, however, for the belt of attenuation, the British fault, and the De Bavay fault, no structural feature appears to have been important in determining the existence of an ore body. ***The ore bodies occur in the favorable beds where those beds are intersected by the belt of attenuation except where the intersection has been strongly disturbed by pre-ore faulting and warping.*** This statement summarizes the main facts of ore occurrence but does not account for variations in the size or quality of the lode from place to place.

The Broken Hill lodes are remarkable in that they continue for more than 3 miles as uninterrupted stopable ore, except for the small gap occasioned by the British Fault. Along this 3 miles they vary greatly in metal content (Pl. 8). Had mineralization been less intense—or if we could consider the base of this graph moved up so that zero tons per linear foot were where 5000 tons per linear foot is now—the Broken Hill ore bodies would be repetitive and "erratic" instead of continuous and persistent. It follows that any new system of ore bodies may be of the repeating kind. The ore bodies of the main line of lode may, as they die out, become repetitive also.

Cross structures to account for variations in the metal distribution along the line of lode would, it was hoped, define narrow east-west belts within which deep or lateral exploration should be confined. The attempts to find such structures have so far been unsuccessful for practical purposes. Peaks in the metal distribution curve cannot, we believe, be explained by any one simple structural relationship, but are the composite effect of many. Buckles, second-order folds, changes of pitch, coincidence of the main shear with certain strong minor folds, variable strength of the main shear, an echelon offsetting of the main shear all appear to have played their part. The presence in some places of large low-grade rhodonitic masses and the localization of ore shoots within the zinc lodes indicate that the variable amount of fracturing from place to place of early gangue minerals during mineralization was important in providing channelways for later sulphides. This more than any other single influence (unless it was sedimentary differences from place to place in the favorable beds) probably accounted for variations in the metal content of the lodes.

Localization of Ore by Intra-Mineralization Fractures

The lodes display abundant evidence that fracturing of the favorable beds during mineralization was a continuing or repeated occurrence. Within No. 3 Lens formation, for example, "garnet quartzite" and "garnet sandstone" masses were invariably fractured, and the fractures were filled with younger lode minerals. All gradations are seen from "garnet sandstone" traversed by a network of tiny sulphide and quartz veinlets to massive sulphide ore with residual remnants of "garnet sandstone" in it. Again, in the British and Block 14 sections, large unreplaced rhodonite masses display similar characteristics. Sulphide ore occurs as shoots controlled by fracturing within these masses which themselves, on a larger scale, are islands in the ore of No. 3 Lens ore formation.

Within No. 2 Lens ore formation in the Zinc

Corporation and New Broken Hill Consolidated mines, the same type of thing is seen in low-grade portions of the lode rich in hedenbergite, rhodonite, and wollastonite. Definite streaks of low-grade ore traverse the lodes in a manner clearly controlled by fracturing rather than by the hospitality or inhospitality of any favorable bed.

In the lead lodes generally, the distribution of fracturing during mineralization appears to explain why some sections of the lodes are better, but mineralization was so intense that there was virtually continuous ore even in the poorer places. Localization of ore shoots by fracturing is best illustrated by the zinc lodes in the Zinc Corporation and New Broken Hill Consolidated mines. Here ore amounts to but a third to a half of the lode formations, and steep ore shoots occur within flatly pitching folds. For example, in the Rhodonitic Zinc Lode where fracturing was early and feeble, only the most favorable thin beds were converted to feebly metallized "garnet quartzite". Where fracturing was stronger and persisted longer, massive rhodonite and hedenbergite with thin residual layers of "garnet quartzite", both traversed by seams of sulphides, occupy the lode formation. Where intense, continuous, or repeated fracturing occurred, the entire formation consists of massive ore containing residual patches of rhodonite. An early to intermediate stage is reflected by large masses of "garnet sandstone" veined by hedenbergite.

The Siliceous Zinc Lode is similar except that large, barren or very low-grade areas of "pegmatite" (hydrothermal replacement quartz and feldspar) exist in place of rhodonite-hedenbergite. Good ore shoots occur on one flank of a fold or as a tabular mass traversing the formation where it is thickened in syncline "I". High-lead shoots in the zinc lodes were possibly governed by very late fracturing, since deposition of galena apparently continued after deposition of sphalerite.

Zoning

There is little recognizable zoning within the Broken Hill ore deposit. The profound mineral differences within the deposit are due to other causes related to the sedimentary strata replaced by ore. No. 2 Lens ore is consistently calcitic and has characteristic Pb-Zn and Pb-Ag ratios from top to bottom and throughout the length and breadth of the lode. No. 3 Lens ore likewise is consistent in its different and characteristic mineralogy and distinctive metal ratios. Each of the two main zinc lodes also is composed of diagnostic mineral assemblages different from those of other lodes. Since the ore beds are closely and intimately folded, No. 3 Lens ore often extends far above No. 2 Lens ore. Also, because of pitch, there is both No. 2 Lens ore and No. 3 Lens ore higher than zinc lode ore. The ore types were clearly dictated by the character of the replaced sedimentary strata regardless of their position with respect to each other or to the source or sources of ore solution.

Some of the progressive changes within the lodes may also be due to variations in the sedimentation of the ore beds rather than to zoning. At the north end of the field the No. 3 Lens ore body is much bigger and more important than the No. 2 Lens ore body, and the zinc lodes are practically non-existent. In the center of the field all but No. 3 Lens ore body have been eroded. In the south end of the South mine and in the Zinc Corporation mine, however, No. 3 Lens ore body has dwindled to very small size. With the diminution of No. 3 Lens ore body No. 2 Lens ore body has become much larger and the zinc lodes have assumed increasing importance.

From the No. 8 level of the Zinc Corporation level of the N. B. H. C., a vertical distance of 1,420 feet and linear distance along pitch of about 3,000 feet, the zinc lodes improve. They contain more ore and more high-lead streaks. Because of the high-silver character of No. 3 Lens ore, these changes result in much more high-silver ore at the north end of the lodes than at the south end. Because of the zinc lodes, there is much more high-zinc, low-silver ore as well as more high-lead, low-silver ore, at the south end. More likely this condition reflects a progressive sedimentary change in the favorable beds rather than a zonal control or ore deposition, although the No. 3 Lens type of ore could have been deposited more profusely at the north end and the No. 2 Lens ore type and the zinc lode ore types at the south end because of temperature and/or other zoning controls. Even less certain is the reason for No. 2 Lens ore

apparently becoming increasingly "rhodonitic" and "wollastonitic" (?) in depth.

One mineralogical change that does seem due to zoning is the increase in the amount of pyrrhotite, especially along the margins and in poorer portions of the ore at the south end of the field. This seems to indicate higher temperature conditions to the south. An increase in the amount of arsenopyrite, also a "high-temperature" mineral, at the south end of the field is suspected (Stillwell, 1926, p. 103).

Metal ratios within any one ore type are amazingly constant throughout the field. Gustafson's impression, shared by Zinc Corporation and New Broken Hill Consolidated personnel (George Fisher, Struan Anderson, R. Hooper, verbal communication), is that there are larger and more numerous zincy spots in the lead ore bodies on the deeper levels of the Zinc Corporation and New Broken Hill Consolidated properties. Like the similar impression that the zinc lodes are becoming more "leady", this is not backed by statistical evidence and could be in error, or correct for a local condition only.

Meager evidence of zoning coupled with the predominant south pitch of the district strongly suggests that the ore solutions moved up the pitch of the folds within favorable strata from some unknown hot magma source to the south.

Classification of the Ore Deposits as to Temperature and Depth of Ore Formation

There is a considerable range of published opinion regarding the classification of the Broken Hill ore deposit according to its temperature and depth of formation. Andrews (1922, 1926) took the extreme view that the lodes as well as the igneous rocks of the district were injected under conditions of great temperature, great pressure, and deep burial as "pressure lenses" in "pressure slacks". Lindgren (1933) classed the deposit as hypothermal.

We are unanimous in our belief that folding occurred at great depths characteristic of plastic deformation, perhaps as deep as 12 to 20 miles, whereas ore deposition occurred long after folding, following an interval of uplift and erosion, at much shallower depths (following emplacement of dolerite dikes), and further that the lodes owe their shapes to the replacement of folded rocks. We are, however, divided as to the emphasis which we place on such evidence as:

1. The first conspicuous act of ore deposition was the introduction of large amounts of "lode pegmatite" characterized by green microcline and quartz, accompanied by silicification and garnetization of the gneiss. Much, if not all, of the quartz and feldspar of this stage replaced the rock rather than intruded it in igneous fashion, as irregular patches in "garnet quartzite" testify. In this early stage occurred the introduction (or recrystallization) of large quantities of rhodonite, johanssenite, pyroxmangite, bustamite, hedenbergite, and garnet, all relatively "high-temperature" minerals. Fibers of tremolite 2 inches long intergrown with quartz and sphalerite, have been found in the Siliceous Zinc Lode. Occasional quartz-biotite veinlets cut garnet sandstone. Considerable amounts of pyrrhotite, arsenopyrite, and löllingnite occur in the ore, often closely associated with hedenbergite. These mineral associations betoken relatively high temperatures of ore deposition.

2. The large size of the ore deposit, the general absence of zoning, and the limited extent of wallrock alteration are characteristic of hypothermal deposits as defined by Lindgren (1933) and Graton (1933).

3. The introduction of tremendous quantities of sphalerite and galena, microscopic tetrahedrite, and some chalcopyrite and other sulphides was accompanied by the introduction of fluorite calcite, and quartz, and the replacement and continued recrystallization of rhodonite and garnet. This mineral assemblage need not be hypothermal, and in fact is frequently mesothermal (Lindgren (1933), Graton (1933).

4. The presence in the ore of such minerals as pyrargyrite, wurtzite, and marcasite suggest distinctly shallow conditions of ore deposition, if indeed these minerals are not supergene.

Burrell (1942) holds that most of the manganese silicates and calcite are of metamorphic origin, although they were recrystallized by the ore solutions. He believes that the evidence of the lode pegmatites and limited wallrock alteration nevertheless places the deposit in the hypothermal group, but that cooling was sufficiently rapid to permit conditions during the latter part of the ore-forming activity to approach mesothermal conditions. He considers

the pyrargyrite, wurtzite, and marcasite to be probably supergene.

Garretty (1943) considers the manganese silicates and also the pyrargyrite to be truly hydrothermal. Gustafson considers the manganese silicates to be hydrothermal and the pyrargyrite to be probably supergene. Both consider the deposit to be hypothermal.

There is little direct evidence as to the temperature of ore formation. Wright and Mawson (Mawson, 1912, p. 310) showed blue lode quartz from Broken Hill to be the "low" type and concluded that ore deposition occurred below 575° Centrigrade. Schwartz (1927) considers that ore deposits containing cubanite-chalcopyrite intergrowths were formed above 400–450° Centrigrade. Stillwell (1926) describes similar chalcopyrite-pyrite-cubanite intergrowths from Broken Hill.

The effects of great pressures on such points on the "geological thermometer" is imperfectly known. According to Graton (personal communication) such points established at low pressure should be raised somewhat where applied to reactions at depth. On the other hand, during the long period of ore deposition, the thermal gradient was steepened by the flow of hot ore solution. Assuming the ores were formed in the 450° C. to 500° C. range and extrapolating from the present thermal gradient of the mines, these figures correspond to maximum depths of 54,000 to 60,000 feet. With the steeper gradient obtaining during ore deposition the same temperature range must have obtained at considerably shallower depths.

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ABSTRACTS OF PAPERS SUBMITTED TO THE NOVEMBER MEETING IN WASHINGTON, D. C., NOVEMBER 16–18, 1950

DETAILED STRATIGRAPHY OF GALENA-DECORAH-PLATTEVILLE SEQUENCE IN UPPER MISSISSIPPI VALLEY*

Allen F. Agnew
U. S. Geological Survey, Platteville, Wis.

Stratigraphic studies in the Upper Mississippi Valley since 1942 have clarified numerous problems related both to the lead-zinc deposits of the Wisconsin-Illinois-Iowa mining district and to the regional stratigraphy.

The Platteville formation, apparently conformable on the St. Peter sandstone, contains the following members, in ascending order: Glenwood shale, Pecatonica dolomite, McGregor limestone, and Quimbys Mill. Quimbys Mill member, the "glass rock" of the miners, thins to the west, as does the Pecatonica. The Platteville is 50 to 75 feet thick.

The Decorah formation, which disconformably overlies the Platteville, includes the following members, in ascending order: Spechts Ferry shale, Guttenberg limestone, and Ion dolomite. Spechts Ferry is "clay bed," Guttenberg is "oil rock," and Ion is "blue" (below) and "gray" beds to lead-zinc miners. All members of the Decorah thin to the east. The Decorah is 30 to 45 feet thick.

The Galena formation, conformable on the Decorah, consists of two dolomite and limestone units of equal thickness, the lower cherty and the upper noncherty. The noncherty unit is called "yellow sandy," the cherty unit is called "drab" by the miners. The cherty unit is subdivided lithologically into six zones, distinguished mainly by the abundance of chert. The Dubuque and Stewartville members, and the upper part of the Prosser member of the Galena fall within the upper, noncherty unit. The Galena, 220 to 230 feet thick, appears to underlie the Maquoketa disconformably.

Regionally, the Galena-Platteville sequence becomes dolomite eastward, toward the Wisconsin Arch. Locally in the lead-zinc district, mineralizing solutions altered these rocks by silicification, dolomitization, and shalification.

Detailed faunal studies are in progress.

USE OF BIOTITE FOR GEOLOGICAL AGE MEASUREMENTS BY THE STRONTIUM METHOD

L. H. Ahrens and F. H. Whiting
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The strontium method for measuring geological age is capable of providing reliable age measurements when applied to rubidium-rich minerals found in pegmatite, notably lepidolite. Such minerals are, however, somewhat rare, and, for the strontium method to be of greater use to geology, it should be capable of application to a common mineral.

In igneous rocks, biotite is the favorite host mineral for rubidium, and in it concentrations of 0.1–0.2 per cent are common. Such concentrations may be determined with satisfactory accuracy using a spectrochemical procedure. At the time of writing, 35 determinations had been made, each in triplicate. In biotite, *total* strontium commonly lies within 0.005–0.02 per cent Sr, of which a significant proportion, namely, 1–40 per cent, is usually radiogenic. Total strontium may be estimated by a spectrochemical method. For an isotope analysis on the mass spectrograph, strontium may be concentrated with reasonable facility.

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EVIDENCE FOR ARIDITY IN WESTERN TEXAS DURING EARLY CRETACEOUS*

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In the Finlay Mountains of Hudspeth County, Texas, an angular unconformity separates sedimentary rocks of the Permian and Cretaceous systems. Locally a band of impure chalky limestone as much as a foot thick has been preserved along this unconformity; the chalky limestone is believed to be of Cretaceous age. Disconformably overlying this band are layers of limestone conglomerate, the lower parts of which contain many angular pebbles with facets or slightly concave surfaces on one side.

The chalky limestone is interpreted as part of an ancient soil profile, probably reworked and similar in origin to lime-enriched zones of the southwestern United States soils, and developed by weathering of calcareous parent material in a semiarid or arid climate. The angular pebbles in the overlying conglomerates apparently were shaped by solution faceting under similar climatic conditions. Thus the inference is drawn that a dry climate prevailed here at some time during the early part of the Cretaceous period.

In other parts of Hudspeth County limestone conglomerate occurs locally in the basal part of the Cretaceous system. Evidently the seas of Cretaceous time advanced northward over a terrain partly covered with limestone gravel. Presumably this gravel would more likely have formed under arid than under humid conditions; in any event its existence is in harmony with the climatic conditions suggested by the fossil soil and faceted pebbles of the Finlay Mountains.

MINERALIZATION IN THE VOLCANO DISTRICT, ELMORE COUNTY, IDAHO

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The gold-silver-base metal-quartz veins and lodes of the Volcano district are located along the south margin of Camas Prairie in Elmore County, Idaho, just west of the Camas County line, 20 miles west-southwest of Fairfield, Camas County. The veins and lodes are fissure fillings with minor replacements intimately associated with granophyric dikes, both of an early Tertiary age, and are localized by an east-northeast shear zone in a quartz monzonite facies of the Idaho batholith. The emplacement of the dikes and mineralized veins was controlled by fractures resulting from the Laramide disturbance. The deposits have been exhumed from beneath a cover of Pliocene rhyolite and Pleistocene basalt.

The vein and lode deposits consist of networks of small quartz seams and stringers with a N. 60°–70° E. trend and steep northwest dips along complex fracture zones. The lodes have been worked for gold, although all contain minor amounts of silver, copper, lead, and zinc.

Wall-rock alteration appears excessive for the small degree of metallic mineralization. Sericitization, silicification, albitization, and epidotization, in that order, have highly altered the monzonitic rock for an average of 25 feet adjacent to the veins and lodes.

PETROGRAPHY OF THE WILCOX FORMATION OF ARKANSAS†

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The mineral composition of representative clays and sandstones of the Wilcox formation of Arkansas was determined petrographically in co-operation with the Division of Geology, Arkansas

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Resources and Development Commission. Samples representing the exposed thickness near Texarkana, Hope, Malvern, and Little Rock were studied and show little variation in mineral composition with stratigraphic position or along the strike of the outcrops for the 140 miles from Pulaski County to Miller County. Representative samples of the clays used in ceramics were analyzed chemically, and their mineral composition was checked by X-ray and differential thermal methods. The principal minerals are kaolinite, quartz, and montmorillonite. Small amounts of muscovite, microcline, zircon, tourmaline, rutile, epidote, ilmenite, and leucoxene are present in most samples. A few grains of kyanite similar to that in the schists of North Carolina are present in some samples and suggest that part of the sediment was contributed from Appalachia. The mineral assemblage indicates thorough weathering of the source rock prior to deposition of the sediments. The kaolin minerals were formed by long-continued leaching by neutral or slightly acid ground waters under favorable climatic and physiographic conditions. The montmorillonite was formed from suitable source rocks by alkaline solutions under conditions of poor drainage. The clay minerals were eroded, mixed with quartz and other minerals, and deposited in the sea which occupied this area during Eocene time.

MESOZOIC ROCKS IN FLORIDA AND GEORGIA*

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Mesozoic rocks occur in the subsurface throughout Florida and the Coastal Plain of Georgia; the larger part is stratigraphic units that belong to the Comanche and Gulf series of the Cretaceous system. Underlying the Comanche series in parts of Florida and Georgia are rocks tentatively classified as being in part Jurassic and in part Triassic. In the northern part of the Georgia Coastal Plain, an irregular outcrop belt of sandstone and shale belonging to the early Upper Cretaceous Tuscaloosa formation borders on the south the crystalline rocks of the Piedmont. In general, two sedimentary facies are recognized in the different stratigraphic units of the Comanche and Gulf series in Florida and southern Georgia. On the one hand, west Florida and south Georgia are occupied by a predominantly clastic facies similar in its broader aspects to the sedimentary rocks of the western Gulf Coast; on the other hand, over most of the southern part of the peninsula, the Cretaceous rocks are an almost continuous nonclastic facies in which alternating layers of limestone and dolomite predominate. Gypsum and anhydrite are important constituents of the Lower Cretaceous formations in south Florida but are rare in the Upper Cretaceous units. In the northern and central parts of the peninsula the two facies merge laterally into each other.

By means of isopachous contours, two slides show respectively the variations in thickness of the Gulf and Comanche series in Florida and southern Georgia. The total volume of the Mesozoic rocks in this area is estimated at 60,000 to 75,000 cubic miles.

"MINERALIZER" LOCALIZATION IN THE TREASURE MOUNTAIN GRANITE, COLORADO

George W. Bain
Amherst College, Amherst, Mass.

The border phases of the Treasure Mountain granite show a concentration locally of metallic, alkalic, and fluorine-bearing minerals in and around pegmatitelike bodies at the top of the mass and also beneath the foundering site of large roof blocks. This post-Cretaceous granite is a plateau type which was intruded upward into the chill zone; the top is at 12,800 feet elevation and has a 300-foot cap of fine quartz porphyry with irregular, coarse pegmatite masses; at 11,000 feet elevation and below, the intrusive is granite porphyry almost to the contact and lacks these pegmatites.

The rim of the pegmatites is transformed to an aplite rock which is quartz porphyry with dis-

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seminations of fluorite, muscovite, chlorite, carbonates, and sparse magnetite, specularite, molybdenite, and pyrite. Vein-shaped masses originating at the pegmatites have the same mineralogy as the disseminations in the pegmatite rims. A zone under the site of foundering for large roof blocks exhibits similar mineralization. The relationships are repeated at several places.

As a generalization, it seems that foundering of roof blocks, to make cupolas on a batholith roof, can be as effective in causing "mineralizer" and metal unmixing as has been crystallization by loss of heat through radiation.

REVISION OF THE PENNSYLVANIAN AND PERMIAN FOOTPRINTS *LIMNOPUS, ALLOPUS,* AND *BAROPUS*

Donald Baird
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A study of original types and new material indicates that the form-genera *Limnopus, Allopus,* and *Baropus* Marsh, footprints of labyrinthodont amphibians, are synonymous. The types of *Limnopus vagus* Marsh (the genotype) and *Limnopus [Allopus] littoralis* (Marsh) [=*Baropus lentus*] from the Upper Pennsylvanian of Kansas are redescribed and refigured; also the types and new material of *Limnopus [Baropus] waynesburgensis* (Tilton) from the Dunkard Permian of West Virginia.

Affinities of three improperly referred species are discussed. *Limnopus? coloradensis* Henderson has been assigned by Gilmore to *Laoporus. Baropus coconinoensis* Gilmore is assigned to *Agostopus,* and *Baropus hainesi* Carman will subsequently be redescribed as a new genus. The analyses of footprint morphology are based on composites of outlines printed direct from latex molds of the types; this method is an innovation in ichnologic technique.

SHONKIN SAG LACCOLITH REVISITED

Julian D. Barksdale
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Restudy of the earlier collected data and re-examination in the field has convinced the author that the gross layering in the Shonkin Sag laccolith is due to differentiation in place from one and possibly two closely connected intrusions of shonkinitic magma. The layer exhibiting exotic crystallization of biotite-augite-sanidine is a syenite pegmatite formed during the early pneumatolytic stage of crystallization. The wider of the hornblende-aegirine syenite dikelets, which cut the pegmatite, represents the consolidation of the magmatic residuum; the narrower ones are the result of solution replacement along cracks. The many sharp contacts between the various rock types in the laccolith are thought to be due to auto injection caused by tectonic movements which involved the laccolithic disc while it was solidifying and which continued after it had cooled.

MORPHOLOGY AND STRUCTURE OF THE SERPENTINE MINERALS ANTIGORITE AND CHRYSOTILE

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Studies with the electron microscope supported by x-ray and DTA data show that natural and synthetic chrysotile are composed of tubelike fibers, whereas antigorite consists of plates and laths. In both instances the morphological characteristics of the artificial materials are better defined than those of the natural minerals. The units of chrysotile always show curvature of the (001) plane parallel to the *a* or *b* axis. In antigorite this curvature is less marked or absent.

Interpretation of the data suggests that antigorite and chrysotile differ morphologically only in the degree of lateral curvature affecting their component units. Evidence indicates that this curvature

is most pronounced where the ideal serpentine composition is obtained, such as in synthetic chrysotile, and decreases with the amount of trivalent ions replacing magnesium in the structure. It is believed that the degree of curvature depends upon (1) the discrepancy in dimensions of the "sheets" which make up the unit of structure, and (2) the strength of the bonds between the units. This is in accord with the theory previously proposed to account for tubular crystals of endellite.

FRANCONIA FORMATION OF MINNESOTA AND WISCONSIN

W. C. Bell and R. R. Berg
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The Franconia formation consists of medium to fine sandstones, most of which are more or less glauconitic, lying above the Dresbach formation and below the dolomites and siltstones of the St. Lawrence. The "Conference Classification" of 1935 proposed a faunal zonation of the Franconia, assigned geographic names to the zones, and called them members. These zones are not rock units and therefore cannot properly be called members.

Actually the Franconia formation consists of five lithic members and displays large-scale intertonguing between two contrasting facies. The finer-grained and more glauconitic of the two facies predominates in southwestern Wisconsin, along the Mississippi River, and as far north on the St. Croix River as Hudson, Wisconsin. It consists of a basal member (Ironton as originally defined by Ulrich) of medium to coarse nonglauconitic sandstone, which is separated from the underlying Dresbach formation by a change in texture. The succeeding members, all of which must receive new names, are respectively a thin highly glauconitic sandstone, a fine-grained micaceous sandstone, and a unit of alternating cross-bedded glauconitic sandstone and nonbedded silty sandstone. In central Wisconsin, and extending northwest to St. Croix Falls, Ulrich's Mazomanie formation constitutes a nearer-shore facies of the upper Franconia, intertongues with it over a wide area, includes within it Berkey's original section of the Franconia, and consists of interbedded nonglauconitic and dolomitic sandstones.

The distribution of faunal zones is largely independent of the lithic units.

LATE QUATERNARY VEGETATION ON NO MANS LAND ISLAND, MASSACHUSETTS*

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Paleobotanical studies of peat deposits on No Mans Land island, Massachusetts, reveal a continuous vegetation sequence that extends back to a pre-forest period following deposition of the last glacial till.

In 1941 and 1948 three individual peat deposits overlying till, and less than 2 m thick, were sampled along the summit of the sea cliff on the south side of the island. In the uppermost 0.5 m of the till there is a closely packed concentration of boulders in a matrix of fine sand with scattered lenses of sandy silt showing poorly defined involutions. This layer is believed to be a congeliturbate formed by frost action before deposition of the overlying peat. The only macroscopic plant remains that it contains are grass and sedge leaf fragments; the pollen and spores are primarily those of sphagnum, ferns, club mosses, sedges, and composites. Tree pollen is rare and consists of spruce and pine with traces of birch and hickory, suggesting that the tree pollen was transported from distant sources.

The environments of peat sedimentation were successively coniferous swamps, ponds, hardwood-alder swamps, and bog meadows. The forest-tree pollen sequence is typical of the southern New England post-glacial: spruce-pine, pine-spruce-fir, mixed hardwoods with pine and hemlock, oak-chestnut-hickory, and pine-oak-beech-hemlock. The uppermost levels of the peats are unusual in

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the clarity of recorded disturbances of the forest in historic time. Pollen of maize and cereals record the island's agriculture of about 50 years ago. Progressive increase in proportion of non-tree pollen to tree pollen in the depositional sequence may be related to restriction of contributing forests by post-glacial marine invasion.

PALEOCENE DEFORMATION IN NORTH DAKOTA*

William E. Benson and Charles R. Golder
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Excavation for the spillway of Garrison Dam in central North Dakota exposed faulted Fort Union strata overlain unconformably by flat-lying sand beds of the same formation. The contact is erosional, and the lower beds have been channeled to a depth of 4 feet. The deformed zone is only about 1000 feet wide and 30 feet thick, but the deformation is intense. The beds, which consist of silty clay and one thin bed of lignite, have been cut by numerous normal and reverse faults dipping 25° to 85°. In places the faults are spaced so closely that the zone is a jumble of small blocks randomly oriented. Folding was a minor factor in this deformation.

Just under the deformed zone is a 3-foot lignite bed that has been warped only slightly. It is cut by two of the normal faults, but maximum displacement was only about 6 inches. The top of this bed was evidently a plane of slipping.

Drill data indicate that the strata under the deformed zone have been warped into a gentle syncline with a closure of about 50 feet. Although the axis of this syncline does not coincide with the strike of the faults, it is suggested that this local warping developed during deposition of the Fort Union formation and produced enough dip to cause gravity faulting in saturated clay beds near the surface. The possibility that this deformation resulted from landslides adjacent to a Paleocene stream channel is regarded as unlikely.

CONGLOMERATE IN THE "CAROLINA SLATES"

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A conglomerate predominately of quartz pebbles can be traced about 8 miles in southwestern Chatham County, central North Carolina. The country rock is "Carolina Slates" of Precambrian or early Paleozoic age and appears to be entirely conformable with the pebble beds. The beds strike N.35° E. and dip 35° SE. The conglomerate is made up of pebble beds ranging in thickness from a few inches to several feet with intervening beds of highly colored very fine-grained, deeply weathered material; the series ranges in thickness from 10 to 50 feet. The quartz pebbles range in size from pea gravel up to 1½ inches in diameter; they are well rounded, although not spherical; their source is unknown. It is not possible to identify what the matrix was originally. The pebbles exhibit some slaty cleavage. The general strike and dip of the cleavage of the "Slates" is parallel to the bedding of the conglomerate. No evidence of organic remains has been observed. This conglomerate gives definite proof of a water-laid series in the "Slates" and definite evidence of the tilting of the "Slate" series after deposition.

THRUST FAULTING IN SOUTHWESTERN MISSOURI

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Proof of the existence of low-angled thrust faults in St. Clair County in southwestern Missouri is presented. These faults are represented by duplication and by elimination of beds along nearly

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horizontal surfaces and also by decollement and imbricate structures. Slices of competent Jefferson City (Ordovician) dolomites have been thrust through at least 60 feet of overlying Mississippian limestones. The term *interthrust* is introduced to describe such thrusts which are geometrically neither overthrusts nor underthrusts.

The north-trending area of known thrust faults is 7 miles long and 2 miles wide. The total horizontal movement of thrusts is not known, but a minimum of 2 miles is postulated. The major faulting was post-middle Mississippian and pre-early Pennsylvanian.

To the west of the thrust faults, approximately 20 square miles of the lower Mississippian is conglomeratic. Many of the included fragments are angular and range in size from a millimeter to 3 feet in diameter. This conglomerate, which heretofore has not been known in the lower Mississippian of Missouri, was derived from the Jefferson City and suggests that diastrophism began before or during the early Mississippian.

STRATIGRAPHY AND PALEONTOLOGY OF THE MISSISSIPPIAN ROCKS IN THE CENTRAL PART OF THE BROOKS RANGE, ALASKA*

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Mississippian rocks of the central part of the Brooks Range were studied by personnel of the U. S. Geological Survey during the summer of 1949 in conjunction with geological investigations of Naval Petroleum Reserve No. 4, northern Alaska. Geology and topography of three areas were mapped, and fossils were collected from a succession of sedimentary rocks having an average thickness of 7100 feet. The stratigraphic succession in each area was measured in detail, and fossils were collected from all parts of the sections with the objective of determining the lithologic and paleontologic zones in the Mississippian rocks of the region.

The Mississippian rocks of this region comprise, in ascending order, a conglomerate, the Noatak formation, and the Lisburne limestone.

The conglomerate, formerly considered part of the Noatak formation, is a sequence of chert conglomerates 3000 to 5000 feet thick. Only fragmentary plant remains, not yet studied, were obtained from this formation, which is believed to be of lower Mississippian age.

The Noatak formation is mostly grayish-black shale and is approximately 800 feet thick. Limestones in the upper part of the Noatak contain faunas resembling those of certain zones of the lower Tournasian in Europe and formations of Kinderhook age in the Mississippi Valley.

The Lisburne limestone is more than 2300 feet thick. Three members have been distinguished. The lower is believed to be of Osage age, and the middle and upper members are considered of upper Mississippian age.

PENNSYLVANIAN CORRELATION IN SOUTH-CENTRAL COLORADO AND NORTHERN NEW MEXICO

Kenneth G. Brill, Jr.
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Two contiguous lithologic units of middle Pennsylvanian age—the upper Clastic member of the Sandia formation, which contains the *Fusulinella* zone, and the lower Gray limestone member of the Madera limestone, which contains the *Fusulina* zone—can be traced for nearly 200 miles from northern New Mexico to south-central Colorado.

In San Miguel County, New Mexico, two members of the Sandia formation are present. *Fusilinella* occurs in the upper Clastic member. *Fusulina* occurs in the Gray limestone member of the Madera limestone, and *Triticites* in the Arkosic limestone member.

Northward the lower member of the Sandia wedges out. In southern Costilla County, Colorado,

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red and gray sandstone of the upper Clastic member intertongues with dark shale of the Belden shale facies which here contains *Mesolobus striatus*. The Gray limestone member, which carries *Fusulina*, contains several thick limestone beds near its base. The upper part of the member consists of thick detrital layers interbedded with thin fossiliferous limestone beds.

Near Bonanza, Colorado, the Clastic member of the Sandia probably forms the base of the section. The Gray limestone member overlies it but contains much detrital sediment.

Near Salida, Colorado, the Clastic member is represented by at least the upper part of the Belden shale. Ostracodes of late Lampassas or very early Desmoines age occur at or near the contact of the Belden shale with the Gray limestone member. The Gray limestone member contains many limestone beds at its base but much detrital sediment above.

ASYMMETRICALLY LOCATED LONGITUDINAL SUBSEQUENT STREAMS IN THE RIDGE AND VALLEY PROVINCE OF WESTERN VIRGINIA AND SOUTHERN PENNSYLVANIA

A. J. Broscoe

A common feature of the elongated rectangular or trellis drainage pattern of the Ridge and Valley Province is the asymmetric location of longitudinal subsequent streams in widely breached, asymmetric anticlines. Such longitudinal subsequents also receive longer tributaries from one ridge than from the other.

Map study and field observations indicate that this feature is associated with unequally high ridges of the anticlinal limbs, the higher ridge being held up by more gently dipping strata. The cause of the asymmetric location of the longitudinal subsequents is the greater height and, therefore, greater length of waste slopes descending from the higher ridge, while the angle of opposing slopes remains the same. The degree of stream asymmetry associated with unequally high ridge crests can be expressed by the following equation: $b = \frac{a - x}{x}$ where a is the sum of the heights of the two ridges above the valley, x is the height of the lower ridge, and b is the ratio of the map distance from the stream to the higher ridge to the distance from the stream to the lower ridge.

The degree to which the equation is actually realized in asymmetrically located subsequents in an area in western Virginia is roughly indicated by the correlation coefficient .706 between 53 pairs of b and $\frac{a - x}{x}$. In an area in southern Pennsylvania, with 41 cases, the correlation coefficient is .503. The lower degree of correlation in southern Pennsylvania is due to greater accordance of ridge crests in the Pennsylvania area than in western Virginia.

PHOTOGRAPHS OF THE ATOMS IN THE STRUCTURES OF MINERALS

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A generalized microscope has been constructed which permits such magnification that the atoms in crystal structures can be seen and photographed. In this microscope, light of short wave length is used as far as the first diffraction image, and then light of a longer wave length is used from this diffraction image to the final image. For such a microscope the magnification contains not only the usual factor of the image to object ratio, but also a second factor consisting of the ratio of the wave lengths of the second to the first kind of radiation. When visible light and x-rays are used for these radiations, this second factor is about 10,000, and the whole magnification is about 300,000 diameters. This is sufficient to enable one to just see the individual atoms of a crystal structure. Unfortunately, a loss of phase occurs when the wave length is changed. This is made up by the use of phase shifters composed of mica of uniform thickness. The apparatus actually used for this generalized kind of microscopy is described, and photographs are shown of the crystal structures of pyrite, marcasite, and KH_2PO_4.

NEW DEVELOPMENTS IN BORE-HOLE PHOTOGRAPHY

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Extensive research in the field of bore-hole photography for the Corps of Engineers during the last 5 years has led to the development of two methods of obtaining complete photographic records of 3-inch borings of extended depth.

One method involves rotation of the camera view at an angular velocity which is always proportional to the velocity of descent of the camera into the hole. Thus the center of the camera view generates a helix of constant pitch. A 16-millimeter film is passed through a curvature-correcting gate at a velocity which bears a constant relationship to the angular velocity of the camera view. A flashlight illuminating system, synchronized with these operations, fires at the proper frequency to provide complete photographic coverage of the bore hole. Recording devices measure the depth and azimuth of the center of each photograph accurately. A prototype camera embodying this method has been fabricated and subjected to field tests.

The other method involves the use of a conical mirror which permits taking 360-degree photographs of the boring. By reversing the process inside a ground-glass diffusion screen of cylindrical shape, a 360-degree projection of the pictures can be observed in undistorted form to natural scale on the outside surface of the cylindrical screen. A contract for the fabrication of a camera and the necessary projection devices embodying this method is now in force. The camera is being designed to operate to depths of 500 feet, and to withstand hydrostatic pressures of at least 200 pounds per square inch. The depth and azimuth of each photograph will be recorded on the film. The camera will be lowered on a steel cable. Its film track and lighting devices will be activated by an outside source of power.

GEOTECTONIC RELATIONSHIPS OF MINERAL DEPOSITS*

W. M. Cady, V. E. McKelvey, and F. G. Wells
U. S. Geological Survey, Washington, D. C.

Some major tectonic provinces show a similar pattern of evolution and consequent distribution of rocks and minerals. The Appalachian and Cordilleran belts, for example, show four principal developmental stages: (1) primary subsidence in two belts, partly separated by a geanticline, accompanied by basic volcanism in the eugeosyncline (belt farthest from the continental block or craton) but not in the miogeosyncline (belt adjacent to craton); (2) diastrophism, mainly in the eugeosyncline and adjoining geanticlinal area where it is accompanied by ultramafic (early) and granodioritic (late) intrusions, and subsidence and sedimentation in secondary basins within the geosynclines; (3) diastrophism, particularly in the secondary basins and underlying portions of the primary geosynclines, accompanied by volcanism and granitic intrusions; (4) differential uplift and block faulting accompanied by basaltic extrusions and alkalic intrusions.

Nonsedimentary mineral deposits of the eugeosyncline include chromite and platinum associated with ultramafic rocks; gold and some silver in quartz veins associated with the granodiorite; mercury, antimony, bismuth, zinc, and minor amounts of lead. Sedimentary deposits include placers and Franciscan-type iron and manganese ores. The secondary basins contain a variety of evaporites, low- to high-rank coal, and oil.

Epigenetic mineral deposits of the miogeosyncline include lead and zinc replacements and disseminated copper ores. Sedimentary deposits include Clinton-type iron, Oriskany-type manganese, phoshate, and, in the younger rocks, evaporites, medium- to high-rank coal, and some oil.

The epigenetic mineral deposits in the post-basement rocks of the craton are characterized by complex mineral assemblages. Sedimentary deposits resemble those of the miogeosyncline except that placers occur near basement uplifts, coal is of relatively low rank, and oil is abundant.

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red and gray sandstone of the upper Clastic member intertongues with dark shale of the Belden shale facies which here contains *Mesolobus striatus*. The Gray limestone member, which carries *Fusulina*, contains several thick limestone beds near its base. The upper part of the member consists of thick detrital layers interbedded with thin fossiliferous limestone beds.

Near Bonanza, Colorado, the Clastic member of the Sandia probably forms the base of the section. The Gray limestone member overlies it but contains much detrital sediment.

Near Salida, Colorado, the Clastic member is represented by at least the upper part of the Belden shale. Ostracodes of late Lampassas or very early Desmoines age occur at or near the contact of the Belden shale with the Gray limestone member. The Gray limestone member contains many limestone beds at its base but much detrital sediment above.

ASYMMETRICALLY LOCATED LONGITUDINAL SUBSEQUENT STREAMS IN THE RIDGE AND VALLEY PROVINCE OF WESTERN VIRGINIA AND SOUTHERN PENNSYLVANIA

A. J. Broscoe

A common feature of the elongated rectangular or trellis drainage pattern of the Ridge and Valley Province is the asymmetric location of longitudinal subsequent streams in widely breached, asymmetric anticlines. Such longitudinal subsequents also receive longer tributaries from one ridge than from the other.

Map study and field observations indicate that this feature is associated with unequally high ridges of the anticlinal limbs, the higher ridge being held up by more gently dipping strata. The cause of the asymmetric location of the longitudinal subsequents is the greater height and, therefore, greater length of waste slopes descending from the higher ridge, while the angle of opposing slopes remains the same. The degree of stream asymmetry associated with unequally high ridge crests can be expressed by the following equation: $b = \frac{a - x}{x}$ where a is the sum of the heights of the two ridges above the valley, x is the height of the lower ridge, and b is the ratio of the map distance from the stream to the higher ridge to the distance from the stream to the lower ridge.

The degree to which the equation is actually realized in asymmetrically located subsequents in an area in western Virginia is roughly indicated by the correlation coefficient .706 between 53 pairs of b and $\frac{a - x}{x}$. In an area in southern Pennsylvania, with 41 cases, the correlation coefficient is .503. The lower degree of correlation in southern Pennsylvania is due to greater accordance of ridge crests in the Pennsylvania area than in western Virginia.

PHOTOGRAPHS OF THE ATOMS IN THE STRUCTURES OF MINERALS

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A generalized microscope has been constructed which permits such magnification that the atoms in crystal structures can be seen and photographed. In this microscope, light of short wave length is used as far as the first diffraction image, and then light of a longer wave length is used from this diffraction image to the final image. For such a microscope the magnification contains not only the usual factor of the image to object ratio, but also a second factor consisting of the ratio of the wave lengths of the second to the first kind of radiation. When visible light and x-rays are used for these radiations, this second factor is about 10,000, and the whole magnification is about 300,000 diameters. This is sufficient to enable one to just see the individual atoms of a crystal structure. Unfortunately, a loss of phase occurs when the wave length is changed. This is made up by the use of phase shifters composed of mica of uniform thickness. The apparatus actually used for this generalized kind of microscopy is described, and photographs are shown of the crystal structures of pyrite, marcasite, and KH_2PO_4.

NEW DEVELOPMENTS IN BORE-HOLE PHOTOGRAPHY

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Extensive research in the field of bore-hole photography for the Corps of Engineers during the last 5 years has led to the development of two methods of obtaining complete photographic records of 3-inch borings of extended depth.

One method involves rotation of the camera view at an angular velocity which is always proportional to the velocity of descent of the camera into the hole. Thus the center of the camera view generates a helix of constant pitch. A 16-millimeter film is passed through a curvature-correcting gate at a velocity which bears a constant relationship to the angular velocity of the camera view. A flashlight illuminating system, synchronized with these operations, fires at the proper frequency to provide complete photographic coverage of the bore hole. Recording devices measure the depth and azimuth of the center of each photograph accurately. A prototype camera embodying this method has been fabricated and subjected to field tests.

The other method involves the use of a conical mirror which permits taking 360-degree photographs of the boring. By reversing the process inside a ground-glass diffusion screen of cylindrical shape, a 360-degree projection of the pictures can be observed in undistorted form to natural scale on the outside surface of the cylindrical screen. A contract for the fabrication of a camera and the necessary projection devices embodying this method is now in force. The camera is being designed to operate to depths of 500 feet, and to withstand hydrostatic pressures of at least 200 pounds per square inch. The depth and azimuth of each photograph will be recorded on the film. The camera will be lowered on a steel cable. Its film track and lighting devices will be activated by an outside source of power.

GEOTECTONIC RELATIONSHIPS OF MINERAL DEPOSITS*

W. M. Cady, V. E. McKelvey, and F. G. Wells
U. S. Geological Survey, Washington, D. C.

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INTRUSION AND GRANITIZATION IN THE BRYSON CITY AREA, NORTH CAROLINA, AND THEIR RELATION TO REGIONAL DEFORMATION*

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Studies in the Bryson City area of North Carolina have clarified certain relationships between intrusion, granitization, and regional deformation in this part of the older Appalachians. Two stages of regional deformation are clearly recognizable; a third is suggested. The first stage followed intrusion of gabbro and peridotite into rocks of the Ocoee series. Both the intrusives and the sediments were folded (first-order folds) and metamorphosed; an axial-plane foliation was developed. Granitization followed and was differentially guided by foliation and bedding of the older rocks. A complex of granitic gneisses about 7 miles long and 2 miles in maximum width was developed.

Further deformation produced second-order folds and related linear structures in both the granitized and the ungranitized rocks. Further granitization may have taken place at this time. Foliation produced in the first stage was folded and crumpled, and slip cleavage systematically related to the axial planes of the second-order folds was developed in places. Granodiorite porphyry dikes along fracture zones in granitic gneisses probably were intruded subsequent to the second stage of deformation. Zones of foliation cutting two of the dikes suggest still a third stage of deformation. Aplite, granite, and granite porphyry dikes, followed by bodies of pegmatite, close the sequence of bedrock units. These rocks are unmetamorphosed and were apparently emplaced in local foci of shearing and faulting.

NATURE OF ORE-LEAD*

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U. S. Geological Survey, Washington, D. C.

Lead is unique among ore metals in that new lead is being created all the time, the product of radioactive decay of unstable uranium and thorium. Three isotopes—Pb^{206}, Pb^{207}, and Pb^{208}—have been generated continuously at definite rates throughout geologic time, but the fourth stable isotope Pb^{204} is not known to be forming on earth from any natural nuclear transformation. Lead in the earth therefore includes an original endowment of all four isotopes augmented by radiogenic increments of only three. Inherent in this situation is a means by which interpretation of the geologic history of natural lead can be attempted.

Such interpretation of ore-lead was attempted by Holmes (1926; 1929; 1937; 1938), who concluded that lead from ores has a uniform atomic weight and therefore only one geologic source. Meanwhile the mass spectrometer was perfected for measuring accurately the relative proportions of the four isotopes. Significant variations in isotope ratios in lead from various ores were thus demonstrated by Nier (1938; 1941), who suggested that ore-lead consists of original or primeval lead contaminated by accretions of radiogenic isotopes.

The isotope determinations that Nier published for some 20 ore-leads have been used chiefly in estimating the age of radioactive minerals and the age of the earth. These data deserve more attention from students of ore deposits. They reaffirm the likelihood that lead-ores originate from diverse sources. They suggest new interpretations, for several of those samples, concerning source of metal or date of metallization. But, especially, they demonstrate need for fundamental geologic investigation of isotopic variations in lead.

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ORIGIN OF TRANSVERSE DRAINAGE OF THE NORTH ATLANTIC SLOPE

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The supposed prevalence of parallel southeast-flowing streams between the Potomac River and the Hudson River, an essential phase of the hypothesis of regional superposition, is in reality an eastern to southern alignment consistently developed at right angles to structure lines. This is a characteristic of transverse drainage throughout the extent of the Ridge and Valley Province and in the adjacent Plateau Province.

The principal areas of transverse drainage and their deduced origin are: (1) Transverse streams in the Plateau Province, the upper North Branch of the Susquehanna River and the upper Delaware River, are due to headward erosion in essentially flat-lying sediments at right angles to the Plateau front; (2) transverse streams across the Nittany anticline are inherited from courses on a Devonian cover over the structure; (3) transverse streams in the Anthracite synclines and in the upper Schuylkill and Lehigh River are the result of inversion of relief; (4) transverse drainage across the two synclinal noses north of Harrisburg, Pennsylvania, Kittatinny Mountain, and the Reading Prong is due to vigorous headward growth of youthful consequents on the western border fault scarp of the upper Triassic Newark Basin which were able to transect these barriers because of their low base level in the subsiding Newark Basin.

Thus, the transverse drainage of the northern Appalachians can be explained by a modification of Davis' hypothesis in which the generally southeastern-flowing drainage of the area was initiated in upper Triassic time by subsidence of the Newark Basin, and developed throughout the Ridge and Valley Province by the normal processes of stream erosion and adjustment in the denudation of folded strata.

DEVELOPMENT AND DISTRIBUTION OF LEACHED ROCK IN THE LAND PEBBLE PHOSPHATE DISTRICT, FLORIDA*

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Box 1390, Plant City, Fla.

Leaching in the Florida land-pebble phosphate district took place predominately at the top of the Bone Valley formation of Pliocene age. The leached zone may be present at other places, where the phosphate deposits are believed to be a weathering residuum of the Hawthorn formation of Miocene age.

The Bone Valley formation is a mixture of sand, clay, and tricalcium phosphate nodules. In the leached zone all or part of the tricalcium phosphate nodules were removed, probably by ground water. The leached product is classified generally on the basis of lithology, and specifically on the degree of removal or alteration of the nodules. The upper part of the zone is an intensely leached, friable, vesicular, white clayey sand from which most of the phosphate nodules have been removed. The lower part is a less intensely leached sand that varies widely in color, porosity, and degree of nodular alteration. This latter type appears transitional between the relatively unaltered rocks in the Bone Valley formation below and the highly altered rock near the top of the leached zone.

The leached rocks are sporadically distributed over approximately 600 square miles of the central part of the land-pebble phosphate district. The lower, less intensely leached part of the zone is most widespread; the best exposures of the intensely leached upper part of the zone are concentrated in a north-northeast-trending belt, 6 to 8 miles wide, between Ft. Meade and Bartow.

Field evidence indicates that most of the leaching took place during the interval following the deposition of the Bone Valley formation and before Pleistocene time but that leaching has continued intermittently to the present.

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Recent studies suggest that reworking of the leached rocks during Pleistocene time resulted in the incorporation of leached zone clay within the lower Pleistocene sands.

TRENTONIAN PALEOGEOGRAPHY IN NORTHWESTERN NEW YORK

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Amherst College, Amherst, Mass.

The orientation of pararipples, mollusk shells, and intraformational folds in the middle Ordovician Kirkfield, Shoreham, and Denmark limestones in the Black River valley in northwestern New York aid in interpreting the nature of seaways and direction of currents. Abundant ripple marks in the Kirkfield and Denmark formations show a northwest-southeast orientation, more apparent in the Kirkfield than in the Denmark. Between opposite ends of the sections, in the Kirkfield, there is an 80 degree change in general direction, more westerly in the northern areas. The formation is thought of as having been laid down in an embayment having a more or less east-west northern margin and a northeast-southwest to north-south eastern one. The embayment was less restricted in Shorehamian and Denmarkian times.

Cephalopod and gastropod shells conform to the orientation of the ripples, but show a two-fold direction due to differences in shape. Endoceroid cephalopods and high-spired gastropod shells are oriented parallel to the currents, smaller orthoceratids are perpendicular. Currents in Shorehamian times are shown to have flowed from southwest to northeast.

Axes of intraformational folds show remarkable parallelism, more than 60 per cent having a strike between N.50°E. and N.70°E. These are interpreted as being the result of excessive loading of the sea floor to the southeast during the opening phases of Taconic orogeny.

THRUST SURFACES ON THE FRONT OF THE CENTRAL WASATCH MOUNTAINS, UTAH

F. W. Christiansen
University of Utah, Salt Lake City, Utah

Evidence is accumulating which indicates that the scarp of the central Wasatch Mountains between Draper and Alpine and probably also north and south of this area is the stripped and slightly modified sole of a major thrust zone. Stripping and laying bare of the thrust surface was accomplished by late Tertiary erosion and probably by local normal faulting on the thrust surface in a reversed direction from the thrust novement. The following is a summary of the evidence supporting this conclusion:

(1) Radical facies difference of contemporaneous strata in the footwall (Weber formation, sandstone 1000 feet thick) as compared with the strata in the hanging wall (Oquirrh formation, sandstone, shale, and limestone 18,000 feet thick).

(2) Presence of a thick zone (300 feet), of mylonite and friction breccia in the fault zone near Corner Creek which is not known to be present in areas where the Wasatch fault alone is exposed.

(3) Presence of a slice of Carboniferous (?) crinoidal limestone, on Precambrian quartzites, on the Wasatch front, south of Little Cottonwood Canyon.

(4) The relatively low (15°–20°), essentially unbroken, slightly convex profile of the Wasatch frontal slope, which represents the inferred footwall thrust surface. Surfaces developed as a consequence of normal faulting in the same area and probably unassociated with the thrust zone are generally steeper.

CORUNDUM DEPOSITS OF MONTANA*

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No other part of North America presents such a rich variety of corundum deposits as central and southwestern Montana. Multi-colored sapphires have been recovered from placers near Helena, Philipsburg, and Deer Lodge, chiefly for use as watch jewels. The Yogo sapphire mine in Fergus County was one of the few important sources of precious stones in the United States and the only deposit in the world where sapphires were recovered directly from igneous rock. Deposits of ordinary corundum in metamorphic rocks in Gallatin and Madison counties have been investigated as possible sources of natural abrasive, but they were small and low in corundum content.

The placer sapphires are chiefly abraded short prismatic pale crystals, which probably were derived from andesitic (?) dikes similar to the dike exposed at French Bar on the Missouri River. At Yogo Gulch the sapphires are platy to equidimensional pyramidal crystals of excellent blue color in an altered analcime-bearing lamprophyre. Reaction of the lamprophyric magma with kyanite-bearing inclusions may have caused precipitation of corundum at an early stage in the cooling of the rock. Later the sapphires were partly dissolved and coated with spinel.

The abrasive corundum deposits are concordant tabular to lenticular bodies enclosed in metamorphosed Precambrian sedimentary rocks. Feldspar, mica, sillimanite, and rutile accompany the corundum, and the texture of the rock ranges from fine-grained and schistose to pegmatitic. These deposits have recently been described as corundum pegmatites, but their form, distribution, and composition suggest an origin by metamorphism of alumina-rich sedimentary lenses.

LUMINESCENCE ACTIVATION OF ZEOLITE MINERALS BY BASE EXCHANGE

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Natural zeolite minerals do not luminesce, but luminescence may be artificially induced by substituting an activator such as Mn^{++}, Pb^{++}, Ag^{+}, or Cu^{++} for part of the minerals' cations (usually Na^{+} and/or Ca^{++}) through base exchange. The powdered mineral is merely soaked in dilute aqueous solution of the activator metal (such as 1×10^{-3} M Cu^{++} solution) at room temperature for as little as 15 minutes. Only 2×10^{-4} per cent (wt.) Cu in stilbite produces luminescence. Luminescence activation is a more sensitive test for base exchange than optical or X-ray diffraction properties, which are altered only after extensive base exchange.

Base-exchanged Cu-zeolites and Ag-zeolites show green and blue cathodoluminescence (under spark-coil discharge or cathode-ray excitation), respectively. After heating at 300°C (dehydrating, to an undetermined extent), some Cu- and Ag-zeolites also develop photoluminescence under ultraviolet excitation (2537A, 3650A). Mn-, Pb-, and (Mn + Pb)-zeolites, which in their normal hydrated state are unresponsive to any excitation source, also develop cathodoluminescence and/or photoluminescence after being dehydrated. When these dehydrated, base-exchanged zeolites are rehydrated, they lose their luminescence.

Luminescence of the zeolites is not a surface adsorption phenomenon, but is related to the entry of the activator ion into the crystal lattice. Removal of the activator ion from the crystal lattice by a reversed base-exchange process eliminates the luminescence. Development of luminescence in base-exchanged zeolites is also a reversible process dependent on the state of hydration or dehydration. The openness of the zeolite crystal lattice and its structural water are significant. All three structure types of zeolites have been investigated: the fibrous (natrolite), lamellar (stilbite, heulandite), and rugged tridimensional (chabazite).

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ISOMORPHISM OF SYNTHETIC FLUORINE-AMPHIBOLES

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In the course of research on the synthesis of asbestos, experimentation was conducted on the crystallization of amphiboles from melts containing fluorine. Major emphasis was given to the study of fluor-tremolite ($Ca_2Mg_5Si_8O_{22}F_2$) and fluor-richterite ($Na_2CaMg_5Si_8O_{22}F_2$). X-ray, chemical, and microscopic analyses indicated a number of isomorphous replacements in the structure by elements that are not observed in natural amphiboles.

The general formula for the complex amphibole group is represented by $(WX)_{2-3}Y_5(Z_4O_{11})_2$. The positions of the W ions in (WO_{12}) co-ordination were filled completely by Na^+, Li^+, and Ca^{++}. Attempts to substitute K^+ resulted in the crystallization of mica to the exclusion of amphibole. The positions of X ions in (XO_8) co-ordination were filled completely by Ca^{++}, Cd^{++}, and partly by Sr^{++}, Ba^{++}, and Na^+. Magnesium ions could not be substituted in 8-fold co-ordination. The Y or (YO_6) positions were satisfied completely by Mg^{++} and partly by Fe^{++}, Zn^{++}, Co^{++}, Ni^{++}, Li^+ and Al^{+++}. In the tetrahedral group (ZO_4) B^{+++} is capable of occupying at least 25 per cent of the 4-fold positions, Be^{++} 12 per cent, and Cr, V, and Al^{+++} undetermined amounts. It was not possible to replace Si^{+4} by Ge^{+4}. This substitution results in the crystallization of Ge-diopside. Attempts to replace F^- by Cl^- in the fluor-amphibole structure by crystallization from melts were unsuccessful.

It was concluded that the extent of isomorphism of fluor-amphiboles is more restricted than in fluor-micas.

The field of stability of fluor-amphiboles is small; consequently, the compositional changes brought about by attempted isomorphous substitutions frequently result in the crystallization of olivine, pyroxene, feldspar, and mica. This conforms with natural magmatic differentiation of phases by crystallization.

CAROLINA BAYS, TRACES OF TIDAL EDDIES

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Gyroscopic properties are inherent in fluids as well as solids because inertia is universal. When a strong eddy is forced to turn about the earth's axis, like a gyroscope, it sets its plane of rotation perpendicular to that axis; a weaker eddy precesses at the speed of rotation of the earth. The plane of a strong eddy stands tilted from the horizontal at an angle equal to the colatitude; the plane of a precessing eddy is tilted at an angle equal to the latitude.

The trace of a strong eddy is an ellipse whose longer (a) and shorter (b) diameters have the proportion $b:a = \sin \phi$, where ϕ = latitude. The trace of a precessing eddy has the proportions $b:a = \cos \phi$. The departure (d, d') of a from the west in the two ellipses is expressed by the equation $d = (90° - \phi) \cos \phi$ or $d' = \phi \sin \phi$.

The elliptical Carolina bays have the shape and orientation characteristic of strong eddies. They lie on all the marine terraces from the Talbot to the Sunderland at altitudes corresponding to the intertidal ranges of the contemporary seas. They are interpreted as the traces of strong tidal eddies.

Similar features near Chesapeake Bay have the proportions and orientation characteristic of precessing eddies. They are interpreted as the traces of weak tidal eddies formed when sea level stood about 5 feet higher than now.

DAM SITES IN JAPAN*

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Japan is embarking on a program involving the construction of 36 major dams for flood-control, hydro-electric, and water-supply purposes. Most of these dams will be far higher than any heretofore constructed in Japan, and several will be among the highest in the world.

Geological exploration for these sites has been very limited. Testing usually includes the drilling of one to a dozen shot-drill holes and a few adits in the abutments. The dams are to be emplaced on various types of rocks ranging from Paleozoic and Mesozoic graywackes, granites, and serpentines to Tertiary andesitic flows and unconsolidated tuffs. Jointing presents a very real problem at most of these dam sites primarily because the Japanese have had little or no experience with the various types of grouting. Greater geological exploration is needed because of the lack of diamond drilling and grouting techniques and because the Japanese have had practically no experience in mixing and placing the enormous quantity of concrete required in these proposed exceptionally high, gravity section dams.

PERMIAN FAUNA OF GLASS MOUNTAINS OF TEXAS AND ITS ECOLOGY

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For 11 years the National Museum has fostered a project designed to make known the Permian fauna of the Glass Mountains. Large blocks, 20 tons of them, have been dissolved in acid to recover the mineralized fossils contained in them. Many hundreds of superb fossils obtained by this method show how the animals lived and give a clue to their environment.

The fauna contains representatives of a majority of the classes, but the most numerous one is the brachiopods. Many bizarre forms such as *Scacchinella*, *Leptodus*, and *Prorichthofenia* are seen for the first time in complete detail. These are reef-forming animals that made banks like oysters. Also seen in perfection are the productids which now show their manner of living and the role of their spines in their welfare. Many of the productids used spines for attachment, but others lived loose on the bottom, the spines keeping them upright on the sea floor.

The combinations and associations of the animals taken with certain types of sediments indicate that the environment in which these creatures lived was that of a shore zone. The bottom was dotted with small clusters or banks of brachiopods and bryozoans which created peculiar local conditions.

SUBMARINE CANYONS BORDERING SOUTHERN CALIFORNIA

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Characteristics of California submarine canyons between Monterey and San Diego differ from land canyons suggesting that their origin is not subaerial: longitudinal profiles are steeper than lower reaches of adjacent land canyons, profiles are more irregular, canyons head near or at sea level but extend to different depths, some greater than 10,000 feet, etc. Geologic data show that the heads of Redondo, Hueneme, Mugu, and Newport canyons cut Upper Pleistocene and Recent sediments, and that no land stream has issued into the Redondo canyon head during the Late

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Pleistocene or Recent. These arguments, with others, suggest that California submarine canyons were cut by submarine processes which are still operating in some canyons.

Wave approach and refraction studies along the California coast, with observations, show that considerable sediment brought to the sea by land rivers is moved along the coast by longshore processes. California submarine canyons occur where (1) a supply of sediment is brought to the canyon heads by these shore processes, (2) a relatively steep offshore slope heads close to shore, and (3) the transporting power of the longshore current slackens usually because of coastal configuration. It is contended that the canyons are eroded by the seaward movement down slope under gravity of sediment accumulated in this way near the canyon heads by some kind of sediment flow, turbidity, density, or suspension current.

VARIATIONS IN CHEMICAL COMPOSITION ACROSS IGNEOUS CONTACTS

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The contact effects resulting from the intrusion of igneous material into various wall rocks are linear compositional changes only in special instances. Large variations in chemical composition from point to point may be present in both intrusive and wall rocks.

A study of these variations by the analysis of closely spaced samples with quantitative spectrographic methods indicates that all of the major rock constituents studied (Si, Al, Fe, Mg, Mn, Ca, Na, and K) are mobile when moderate temperatures and concentration gradients are present. Migration of material is believed to take place late in the cooling history by diffusion along mineral boundaries. The compositional variations resulting from this transfusive migration of hydrated ions are often sufficiently large to mask any compositional changes due to earlier reactions.

The chemical variations found can be related to the original compositions of the wall rock and intrusive material, and to the cooling history of the system. No variations in chemical composition are found across contacts between chemically identical rocks. Generally smooth and continuous variations occur across contacts between rocks of different original composition which have been held at high temperatures. Highly irregular variations are found when the intrusion and wall rock were compositionally different and steep thermal gradients existed. These latter variations may show geochemical culminations and depressions, are wavelike in form, and die out in both directions from the contact zone.

PLANT REMAINS FROM THE ARKANSAS BAUXITE

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Well-preserved, marcasitized plant remains have been obtained from bauxite in pits of the Alcoa Mining Company, Bauxite, Arkansas. The plant remains occur in the upper portion of the bauxite directly below lignite of the Wilcox formation (Eocene). The remains are in the form of slender cylinders made up of three layers of cells with a wall of moderate thickness. These cells are undifferentiated except in places where there are slight constrictions in the cylinders. These constrictions are formed by a definite modification of the cell walls. Detailed study has failed to reveal the classification of these plant remains.

ARENACEOUS FORAMINIFERA FOUND WEATHERED FREE FROM THE SILURIAN OF MISSOURI

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About 15 years ago the senior author, while making a study of the Silurian of Ste. Genevieve County, Missouri, collected a quantity of weathered material from the *Pisocrinus* zone at the base

of the Bainbridge formation. The larger fossils in this material have been studied, but the smaller screenings were examined only this past winter. When the junior author examined this finer material, he found numerous specimens of arenaceous Foraminifera. Specimens of *Ammodiscus* and *Lithotubia* species were especially common. Some 20 species described from this region have been identified. It is believed that this is the first report of Silurian arenaceous Foraminifera being found without the aid of acid reduction.

Many of the specimens show distortion. This would seem to indicate that the original cementing material was flexible and therefore was more likely chitin and not silica or calcium. If this is true, then some of the species erected by the senior author and other writers on shape alone may not be valid.

SNAKE RIVER REGION OF WESTERN WYOMING

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The chief contribution of this report is a series of fifteen-minute quadrangle geologic maps concerning all or part of the area of the Gros Ventre, Jackson, Teton, and Irwin topographic quadrangle sheets of the U. S. Geological Survey. In addition to the geologic maps, a series of tectonic maps will show the progressive evolution of the region in Cretaceous and Tertiary times.

Sharp uplift occurred in the Cordilleran geanticline immediately to the west in latest Jurassic and again in early Cretaceous time, and conglomerates were shed eastward. In the region to the west in Idaho in latest Cretaceous and early Paleocene, the large-scale Bannock eastward thrusting occurred. This was followed immediately in late Paleocene and early Eocene by thrusting in front of (east of) the Bannock; the St. John, Absaroka, and Darby thrust sheets rode eastward. The middle and upper Cretaceous formations were deeply eroded and furnished much of the clastic material for the sands and shales, mostly of late Paleocene age, which accumulated in a trough east of the Darby thrust.

A third episode of thrusting then occurred east of the Darby, and the Jackson and related thrusts rode eastward over the late Paleocene sediments. Gravels and sands of mid-Eocene (?) age were then shed over the region in front of the new thrusts. New thrust sheets (a fourth episode) broke out of the older thrust complex to the west and overrode the mid-Eocene (?) sediments eastward. Also, the Gros Ventre-Teton block rose and was thrust steeply southwestward against the eastward and northeastward-moving Jackson thrust, and over the mid-Eocene (?) conglomerate.

In latest Miocene, northerly trending normal faults cut the thrust complex and brought into relief such features as the Tetons, Jackson Hole, Grand Valley in Idaho, and the Hoback Range.

REVISED CLASSIFICATION OF THE MIDDLE DEVONIAN DETROIT RIVER GROUP

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The succession of Detroit River formations above the Sylvania sandstone as given by Lane, Prosser, Sherzer, and Grabau has been a doubtful matter in the minds of several geologists for many years. However, no evidence has been obtained to prove that Lane and his associates were incorrect in believing that the Sylvania sandstone is succeeded respectively by the Flat Rock dolomite, Anderdon limestone, Amherstburg dolomite, and Lucas dolomite.

Present studies indicate that the oldest unit of the Detroit River group, the Sylvania sandstone, is succeeded respectively by the Amherstburg dolomite, the Lucas dolomite, and the Anderdon limestone. The Flat Rock dolomite of Sherzer and Grabau cannot be distinguished in outcrop or in well borings as a distinct formation. For this reason and because the strata of this dolomite with

little doubt are a part of the Amherstburg dolomite, it is logical to drop the name Flat Rock dolomite from the stratigraphic nomenclature. The Amherstburg dolomite, which is characterized by numerous corals and certain species of brachiopods, is overlain by the Lucas dolomite, the most diagnostic species of which are *Acanthonema holopiforme* Sherzer and Grabau, and *Murchisonia subcarinata* Grabau. The Anderdon limestone, the uppermost formation of the group, contains *Pleurotrochus tricarinatus* Grabau, several other diagnostic and undescribed species of gastropods, and *Conocardium sibleyense* LaRocque.

FAUNAL MIGRATIONS AND MISSISSIPPIAN-PENNSYLVANIAN PROBLEM

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Varied marine fauna comprising 185 species occurs in the Springer series of Oklahoma, which shows nearly balanced affinities to both Mississippian and Pennsylvanian forms of America and the World. However, when considered by groups, the encountered bryozoans, most brachiopods, and ostracods show greater affinity to American Mississippian than Pennsylvanian forms; while some productids, pelecypods, and gastropods show greater affinity to the Lower Carboniferous forms of British Isles.

Conversely, Hind discovered in 1908 the presence of a number of "American Pennsylvanian" pelecypods and gastropods in the basal Millstone Grit of Scotland, and the present revision sustains his general conclusion of their strong American affinity, though not with our Pennsylvanian, but rather with late Mississippian forms, from which the Pennsylvanian forms undoubtedly evolved.

The combined evidence indicates the survival into early post-Mississippian (Springer) time of a number of both American and English forms, which was accompanied by wide intermigration of their most active representatives, particularly the mollusks. This fact suggests opening of sea lanes for their migration across Northern Atlantic, which apparently was a result of a cycle of major orogenic events. Thus, the major intermigration seems of great significance in selection of systemic boundary between Mississippian and Pennsylvanian of America, and also indicates its apparent contemporaneity with the boundary between the Lower and Upper Carboniferous of western Europe.

SELECTED PETROGENIC RELATIONSHIPS OF PLAGIOCLASE

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The following selected conclusions are drawn: (1) Current feldspar curves are not satisfactory. We offer new curves which incorporate some improvement. (2) New analyses on carefully prepared material reveal a very low potash content in plagioclase. (3) Perthitic feldspars are composed of relatively pure feldspar species intergrown. (4) The refractive indices offer the best approach to micro identification. (5) Polysynthetic twinning develops with the elimination of zoning and is consequent on it. (6) Plagioclase feldspar, exsolved from potash feldspar to form perthite, may be highly mobile and replace orthoclase feldspar on a large scale at points of concentration, or may collect to form nepheline syenites. (7) Lamprophyres are a deutericlike product of granites derived locally. (8) Lamprophyres are the source rocks of pitchblende. (9) The lamprophyre-bearing fluorite areas of Illinois and Arkansas are promsing prospecting ground for uranium. (10) Many Precambrian granites originated through feldspar augen. (11) Criteria are offered for the recognition of the quantitative role of liquid in the origin of feldspathic rock. (12) Most granitic bodies studied by us are only shallowly uncovered and reveal only metasomatic phases.

STRATIGRAPHY AND METAMORPHIC RECONSTITUTION OF PARTS OF THE GRENVILLE SERIES IN THE NORTHWEST ADIRONDACKS: A REPORT OF PROGRESS*

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Although most of the metasedimentary rocks of the Grenville Series in the northwest Adirondacks have been profoundly reconstituted, stratigraphic relicts exist which enable a coherent, predictable succession to be reconstructed. The pre-metamorphic metasedimentary sequence in the Balmat-Edwards region was perhaps 9300 feet thick; 15 relict units are identifiable at points along the lithologic trend for 10 or more miles, and many smaller subdivisions are recognizable locally. Stable-shelf facies consisting of thin quartzose beds in thicker dolomite zones and a siliceous, sodic shale (tuff?) predominate.

Reconstitution of some dolomite units involved large-scale dedolomitization. The magnesium was widely redistributed and was fixed in assemblages of quartz-diopside-serpentine, tremolite-anthophyllite-serpentine-talc, and granitized hornblende-andesine amphibolites. Variations of the above assemblages may include scapolite, phlogopite, chlorite, calcite, feldspar, hexagonite-tourmaline, anhydrite, hydrogen-sulfide, and graphite. Important constituents added to and irregularly distributed through the marble include alkalies, manganese, fluorine, chlorine, titanium, phosphorus, silicon, water, and locally zinc, lead, and iron sulfides. Calcium and carbon dioxide, especially, were removed.

The thick shale (tuff?) unit was commonly altered to a quartz-biotite-sodic andesine-almandite-microcline migmatite that locally contains sillimanite-bearing facies. Other, granitized portions were progressively enriched in alkalies and depleted in iron, magnesium, and calcium; these granitic rocks include gneissoid augen, equigranular alaskitic, granulitic, and quartz syenitic types.

Many bodies of the reconstituted rocks tend to follow the original bedding, but other bodies are irregular and blur or obliterate the bedding.

Although of regional scope, the reconstitution was an intricate composite of "contact" and "regional" metamorphism.

LATE QUATERNARY FAUNAL SUCCESSION IN THE SOUTHERN HIGH PLAINS

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Fossil collections from the southern High Plains reveal an interesting succession among extinct species of late Quaternary mammals. In an extensive excavation near Lubbock, Texas, collections were made from five superimposed fossiliferous strata, of which only the lowermost stratum contains a typical late Pleistocene assemblage. In the lower member, remains of mammoth and *Equus* are comparatively common, while remains of *Bison antiquus* (or *B. taylori*) are comparatively rare. In the second member, remains of *Bison antiquus* are exceedingly abundant, but mammoth, *Equus*, *Camelops*, and other large typical Pleistocene forms appear to be absent. The uppermost stratum contains great numbers of *Bison bison*, but not *B. antiquus*. Bison bones from intermediate beds are as yet not positively identified. A similar condition obtains in another large excavation near Covis, New Mexico, and in numerous other High Plains sites where smaller collections have been made.

The sediments containing the large concentration of bison bones indicate a cool and moist climatic stage. Such conditions should have been as favorable for such animals as the mammoth and horse as for the bison. It seems likely that great migrations of *Bison antiquus* into the southern plains

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may have caused a rather sudden depopulation of other large Pleistocene forms from the region. Excavations made on the Gulf coastal plains indicate that horse, mammoth, sloth, and other forms survived quite as long in that region as did the bison.

SOME FEATURES OF THE SECONDARY REDISTRIBUTION OF URANIUM IN OXIDATION ZONES

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The problem of finding uraninite-bearing primary veins involves a careful consideration of the redistribution of uranium in areas of intense oxidation.

Secondary uranium phosphates and sulfates can be formed in at least two ways—as the result of the reconstitution of uraninite in primary veins or by ground-water action on uranium-bearing accessory minerals in igneous rocks. Such uranium deposits commonly are found in or near fractures cutting intrusive rocks, and have been formed under semiarid or arid climatic conditions.

Suggested criteria for determining the presence of primary uraninite-bearing veins in association with deposits of these secondary minerals have been established for deposits in Portugal and the Marysvale district in southwestern Utah: (1) the presence of uranium-bearing minerals which include bases metal in their lattice, (2) rigid structural control by normal and reverse faults, (3) the relationship of uranium minerals to zones of hydrothermal alteration, and (4) the association of typical mineral assemblages including limonite, quartz, hematitic jasper, clay minerals with distinctive base-exchange properties, sericite, and other secondary minerals. Deposits of secondary uranium minerals in parts of the Mojave Desert area, California, exhibit characteristics that differ markedly from those described above and are believed to have resulted from redistribution of uranium from accessory minerals of granites by ground-water action.

It is believed that the suggested criteria should be applied to known torbernite-autunite deposits in other semiarid or arid areas of the world.

HENDERSON DOME, A UNIQUE STRUCTURE IN NORTHWESTERN PENNSYLVANIA

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The Henderson dome, located south of the village of Henderson in the eastern part of Mercer County, Pennsylvania, is roughly circular in outline with a closure of about 150 feet on the Homewood sandstone of the Pottsville and 180 feet on the Venango First Sand of the Upper Devonian. The diameter is about 5 miles. The structure is unique for this part of Pennsylvania from the standpoint of both shape and amount of closure.

In the Maude Davidson No. I well, drilled into the Beekmantown dolomite under the dome, the lower part of the Clinton group, the entire Albion series, and the Queenston red shale are missing; their places are taken by much-fractured gray shales of Upper Ordovician, Reedsville, lithology. In contrast, the section from the Pottsville through the Lockport dolomite is normal both in this well and in one 1800 feet southeast of it. Eleven miles south of the dome, in the Jessie G. Hockenberry No. 1 well, the Albion series and Queenston shale have a combined thickness of 1250 feet. In the Davidson well the interval from the base of the Lockport to the top of the Trenton is 2720 feet, while in the Hockenberry well it is only 2625 feet. The elevation of the top of the Trenton with respect to sea level appears to be normal when the regional dip is taken into consideration.

The cause of the difference between the Davidson and the Hockenberry sections is believed to be tectonic rather than stratigraphic. It is suggested that a tectonic intrusion of Reedsville shale along an incipient fault locally pushed aside the Albion and Queenston and produced the dome.

HYDROTHERMAL URANIUM DEPOSITS NEAR MARYSVALE, PIUTE COUNTY, UTAH

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The deposits are 3–4 miles north of Marysvale, Utah. They are near and at the border of a Tertiary quartz monzonite stock and rhyolite agglomerates. Both rocks are hydrothermally altered and contain fluorite. Pulverulent uraninite in association with very fine-grained pyrite has been found at a depth of about 60 feet in veinlets ranging from capillary size to more than an inch in width. Secondary ore minerals that have been identified thus far are autunite, schroeckingerite and uranophane.

JUNE 1950 FLANK ERUPTION OF MAUNA LOA, HAWAII*

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Following the 1949 summit eruption, magma apparently remained high under Mauna Loa as indicated by persistent fuming. A distinct easterly tilt commenced about March 1, 1950, indicating tumescence of the mountain. The easterly tilt and apparent high position of the magma suggested that the interval between the 1949 outbreak and the succeeding flank eruption might be less than the 18-month average for the last 70 years, and that the outbreak might occur during 1950. Prior to May there were no positive indications favoring either the northeast or the southwest rift as the site of the next eruption. During May 102 earthquakes, more than three times the normal monthly average, were recorded. The majority originated along the southwest rift of Mauna Loa near the summit. The combined evidence led to an announcement issued on May 29 of the volcano's uneasiness and to the prediction that if eruption occurred it would be on the southwest rift.

The eruption began on June 1 high on the southwest rift, which cracked open downslope along a zone 13 miles long. Most of the lava issued from two fissures 1.7 and 3 miles long at altitudes of about 10,000 and 8500 feet respectively. Six main flows were produced; three westward-moving flows reached the ocean. Vent temperatures of 1050° C were observed. Lava flowed freely 11 miles downstream at temperatures ranging from 820 to 950° C. After June 12 lava output declined sharply, as did seismic activity. The eruption ended June 23.

COMMENSALISM OF A NEW ORDOVICIAN TETRACORAL WITH A BRYOZOAN?

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The mid-Ordovician Plattin limestone near St. Louis, Mo., has yielded a silicified ramose bryozoan zooarium on which are located eight calyces; these appear to represent a primitive tetracoral unlike any previously described. The corallites are represented by various stages of ontogeny. The epitheca, instead of completely encircling the calyx as in ordinary tetracorals, has failed to develop over the surface of the bryozoan zooarium; the calyx is thus partly defined by epitheca, partly by the skeleton of the bryozoan colony. In addition, the bryozoan encrusted the outer epithecal surface of the older corallites. The ridgelike septa are added bilaterally. Poor preservation prevents the identification of the bryozoan.

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CHALCANTHITE BY THE X-RAY PRECESSION TECHNIQUE

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This paper outlines the X-ray precession technique as applied to determining the geometry of the lattice of a triclinic crystal. While the orientation of a triclinic subhedron is less simple for the precession technique than for the Weissenberg, once it is secured the angular constants are much more easily obtained and are far more accurate. The necessary three angular and three linear constants are given from photographs made from a single setting: the results are compared with previous goniometric and X-ray studies. The 1-level precession photograph is similar to the Goldschmidt gnomonogram except for scale; this will be illustrated by 0- and 1-level pictures taken on a single film.

SEDIMENTARY AMPHIBOLITES IN THE VAN HORN MOUNTAINS, TEXAS

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Amphibolite, biotite amphibolite, epidote-biotite amphibolite, biotite-anthophyllite amphibolite, anthophyllite amphibolite, almandine amphibolite, epidote amphibolite, and epidosite are found in the Mica Mine area of the Van Horn Mountains, Texas. The amphibolites occur with biotite schists in thin beds and lenses in a thick Precambrian feldspathic quartzite-muscovite schist sequence. Distribution, varied composition, layered character, associated rocks, and transition rocks demonstrate a sedimentary origin. These rocks were originally ferruginous dolomitic marls and ferruginous shales in a sandstone and shale sequence.

Analyses of representative rocks are plotted on ACF diagrams. With low Na_2O, high Fe_2O_3, and excess CaO, epidote takes the place of anorthite. Almandine forms in rocks with excess Al_2O_3 if MgO and FeO act as separate components. With a deficiency of Al_2O_3 ferro-anthophyllite forms instead of almandine. With available K_2O and Al_2O_3, MgO and FeO may act as two components to form biotite and almandine or as one component to form biotite and (when K_2O and Al_2O_3 are exhausted) ferro-anthophyllite.

On Vogt's ACF diagram the rocks fall in the "sedimentary series", corroborating field evidence of sedimentary origin.

PLEISTOCENE STRATIGRAPHY OF EASTERN SOUTH DAKOTA*

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Mapping of Pleistocene deposits in South Dakota has revealed direct evidence of Wisconsin glaciation and at least two pre-Wisconsin stages of glaciation. Indirect evidence strongly suggests that the younger pre-Wisconsin deposits are of the Illinoian stage, and the older are pre-Yarmouth and may include deposits of both the Nebraskan and Kansan stages.

Yarmouth interglacial sediments and the Loveland loess, now generally regarded as Illinoian, have been identified. Deep weathering profiles record the Sangamon interglacial age.

Bodies of coarse alluvium originating far to the west are correlated with the Holdrege, Grand Island, and Crete formations of Nebraska geologists; they are thought to date from the Nebraskan, Kansan, and Illinoian glacial ages, respectively.

The Wisconsin section includes four substages correlated with the Iowan, Tazewell, Cary, and Mankato. Three of them are represented by both till and loess; the Tazewell is distinguished from

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the Iowan on topographic evidence only, and the two substages are believed closely related in time. The Cary and Mankato substages constitute a second closely related pair.

The successive Wisconsin ice sheets flowed into South Dakota from the north and formed a prominent lobe controlled by the James Valley lowland. Each sheet was less extensive than its immediate predecessor. The extent of each and the complex systems of end moraines related to it are shown on a map, scale 1:500,000, as yet unpublished.

STATUS OF CLASSIFICATION OF PALEOZOIC NAUTILOIDS

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Twelve orders of nautiloids are being elsewhere proposed, replacing the four orders of Hyatt (1900) which are no longer usable. The classification is carried out to families, and the more important genera are listed. The first three orders, the Ellesmeroceratida, Actinoceratida, and Endoceratida, have already been traced, as have the Ascoceratida (= Mixochoanites). The Michelinoceratida is remarkable chiefly for the development of cyrtochoanitic structure three times in its history, and the tracing to this line of deviations from the typical orthoconic form. The Oncoceratida undergo a first expansion in the Ordovician, persisting as *Oonoceras* into the Silurian, where a second expansion occurs. Evidence is presented indicating that Silurian forms homeomorphic with some Ordovician genera are actually developed from *Oonoceras* in Silurian time. Many new generic names are required for the placing of the 300 species of *"Cyrtoceras"* of the Silurian of Bohemia, and emendation of old genera is required. The Devonian Acleistoceratidae and Brevicoceratidae stem from the Silurian oncoceroids. The Silurian Trimeroceratidae and Tetrameroceratidae are traceable to oncoceroids, but the true Phragmoceratidae are traceable into the Discosorida through the Cyrtogomphoceratidae. The problem of the origin of the discosorids is discussed. Most coiled forms are included in the Tarphyceratida, Barrandeoceratida, Rutoceratida, and Nautilida. The development of these groups in the earlier Paleozoic is outlined. Remarkable is the development of cyrtochoanitic structure three times in the Barrandeoceratidae, in the Uranoceratidae, the Apsidoceratidae, and in the Rhadinoceratidae. The origin of the Rutoceratida is obscure, but it apparently gave rise to most forms of the late Paleozoic of angular whorl and nodose or lirate exteriors. General aspects of the evolutionary pattern are discussed. Neither shell form, shape of the segments of the siphuncle, nor its internal deposits are in themselves reliable guides to relationship. Transitions among all these characters can be traced on the basis of genera which are essentially intergrading, and permit detailed diagrammatic representation of the evolution of the cephalopods in the Paleozoic.

SURFACE FEATURES OF CHERT AS STUDIED BY THE ELECTRON MICROSCOPE

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Electron microscope study of fracture surfaces of chert, using the replica technique, has shown that at least two and possibly three types of surfaces are present. Specimens which under the light microscope consist of microcrystalline quartz (minute, equant grains) show sharply defined polyhedral blocks with smooth, slightly curved faces—exactly like the shapes occupied by the air cells in soap froth. Arkansas novaculite, a very homogeneous type of chert, possesses this type of surface to a marked degree. Specimens which under the light microscope are composed of chalcedonic quartz (radiating fibers) have a more or less spongy surface, with no evidence of fibrous character when examined with the electron microscope. The sponginess is caused by the presence of abundant spherical water-filled bubbles, all very nearly 0.1 micron in diameter. These bubbles impart a brown-

ish color to the chalcedonic quartz as seen in the light microscope and decrease the density and refractive index (due to the Christiansen effect), in proportion to their abundance. Chalcedonic quartz without bubbles has the same refractive index as normal quartz. The properties of chert and chalcedony are adequately explained by the hypothesis that is consists of fine-grained quartz plus a variable quantity of free water in the form of distinct bubbles; there is no evidence of admixed opal.

IMPORTANCE OF EXCHANGEABLE MAGNESIUM IN THE STUDY OF MONTMORILLONITIC CLAYS*

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In calculating the formulas of members of the montmorillonite group all the magnesium is generally assigned to the Al layer. However, determination of exchangeable cations in 16 montmorillonitic clays, 12 of them the identical specimens for which analyses were quoted by Ross and Hendricks (U. S. Geol. Survey Prof. Paper 205-B), showed that in all of them some of the magnesium was exchangeable, the amount ranging from 0.11 to 1.62 per cent. In two samples exchangeable magnesium amounted to about one third of the total magnesium. These results indicate that the presence of exchangeable magnesium in the montmorillonitic clays is more common than is generally recognized.

Ross and Hendricks, assigning all magnesium to the Al layer in calculating the formulae of montmorillonites, found that the number of ions in octahedral co-ordination ranged from 2.02 to 2.24. However, a recalculation of the formulas of some of these samples on which exchangeable cations were determined showed that, when total magnesium is corrected for exchangeable magnesium and only nonexchangeable magnesium is assigned to the Al layer and when the determined rather than an average base-exchange capacity is used, the number of cations in octahedral co-ordination does not exceed 2.02, even in those samples in which the number of cations is as much as 2.13 when all the magnesium is assigned to the Al layer. Apparently, in montmorillonite then, substitution of Mg for Al in the Al layer is ion for ion, with no extra ions added in an effort to ward internal compensation of charge.

HIGH-TEMPERATURE X-RAY STUDY OF THE POLYMORPHISM OF $MgSiO_3$

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An investigation of the polymorphic inversions of magnesium metasilicate ($MgSiO_3$) has been made with the aid of a high-temperature X-ray spectrometer furnace. This study, which involved the use of both natural and synthetic material, has yielded results which differ considerably from those of previous investigators. On the basis of these results, a new scheme of relations between the three crystalline forms of $MgSiO_3$—enstatite, protoenstatite, and clinoenstatite—is proposed.

SYNTHESIS OF STAR SAPPHIRES AND RUBIES

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The properties of synthetic star sapphires and rubies manufactured by the Linde Air Products Company are described. The asterism is produced by the exsolution in oriented position of rutile needles from an initially homogeneous solid solution of titanium in corundum single-crystals grown by the Verneuil process. The initial solid solution contains about 0.06 to 0.2 atomic per cent of

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Ti^3 in substitution for Al, together with about 1.4 per cent Cr^3 and about 0.3 per cent Fe^3 as pigmenting material in ruby and sapphire, respectively. The clear, homogeneous boules are annealed at about 1900° C to remove strain and are then heated for 2 to 72 hours in an oxidizing atmosphere between 1500° and 1100° to induce precipitation of TiO_2. The length of the precipitation treatment increases with decreasing temperature. Precipitation does not occur over about 1500°, and exsolved rutile can be dissolved by heating to somewhat over 1500°. The crystal chemistry of the precipitation is discussed, and criteria for the recognition of synthetic asteriated corundum are indicated.

CRYSTAL STRUCTURE OF CLAUDETITE (MONOCLINIC As_2O_3)

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The unit cell of claudetite has been determined by M. J. Buerger to be $a = 5.25$ Å; $b = 12.87$ Å; $c = 4.54$ Å $\beta = 93°49'$ and the space group determined to be $P2_{1/n}$. The cell contains $4As_2O_3$. Due to the darkening of the general radiation streak on the c axis zero level Weissenburg in the vicinity of the (030) reflection, doubt was cast on the existence of the two-fold screw axis (2_1). The presence of the 2_1 was confirmed by the comparison of the Harker-Patterson syntheses P(xoz) and P(x½z). From these syntheses and from Patterson projections on (001) and (100) the eight arsenic atoms were found to lie in two general four-fold positions. One set is at $x = .27$, $y = .10$, $z = .03$ and its symmetry equivalents and the other set at $x = .35$, $y = .35$, $z = 0.00$ and its symmetry equivalents. Electron density projections were constructed from those reflections whose phases were unequivocally determined by the location of the arsenic atoms. From these projections the locations of the oxygen atoms could be roughly determined. These are being refined by further electron density projections and intensity checks.

STRATIGRAPHY OF THE LATE PLEISTOCENE LOESSES IN KANSAS

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Late Pleistocene deposits in Kansas consist predominantly of a sequence of loess sheets, each of which terminates upward in a soil profile. The loess sheets are classed in Kansas as Loveland, Peoria, and Bignell silt members of the Sanborn formation. Stratigraphic position, contained fossil mollusks, morphology of the Loveland (Sangamon) soil in its upper part, and the *Citellus* vertebrate faunal zone establish correlation of the Loveland in Kansas with Loveland in Nebraska and with the type section in western Iowa. The Peoria, which generally overlies the Loveland in Kansas, blankets much of the upland and high terrace areas of west-central, central, and northern Kansas. It is a massive, uniform, yellowish-tan, fossiliferous silt, attaining a maximum thickness of more than 100 feet, and is terminated upward by the Brady soil. The Peoria of Kansas is correlated with Peorian loess of Nebraska and Iowa, and with the Farmdale and Peorian (Iowan and Tazewell) loesses of Illinois by extensive molluscan faunas, stratigraphic and physiographic position, and morphology of buried soil profiles. The Bignell loess (late Wisconsinan) is the youngest loess on the uplands of Kansas. Its distribution is restricted, but correlation of the Kansas material with the type Bignell loess of southwestern Nebraska is demonstrable by its position above the buried Brady soil profile and its contained molluscan fauna.

NORTHERN MIDDLE DEVONIAN SEDIMENTARY SOURCE FOR THE SHARON CONGLOMERATE OF NORTHEASTERN OHIO

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Sharon conglomerate, the basal Pennsylvanian bed in northeastern Ohio, is dominantly a pure (95+% SiO_2) medium-grained quartz sandstone with a few pebble layers or scattered pebbles.

Laterally the sandstone grades into a series of narrow conglomerate belts 10 to 50 feet thick. Trend of these belts and cross bedding in the whole formation indicate a northern source for the clastic material and also deposition in a deltaic type of deposit. The literature states that the Sharon pebbles are all "vein quartz" and suggests the erosion of an igneous complex in Canada. Discovery of pebbles composed of quartzite, sandstone, conglomerate, and rotten limestone indicates that the source was at least partly sedimentary; the high purity suggests that it was mainly or wholly sedimentary. Pebbles containing identifiable fossils indicate that this sedimentary series was, at least in part, middle Devonian. The fossils were mostly rugose or tabulate corals, but bits of trilobites, brachiopods, and gastropods were found. Six corals, one brachiopod, and one gastropod were identified, all indicating Middle Devonian (Onondaga-Hamilton) age. The exposed section to the north in Canada contains all the necessary variety of rock types to make the Sharon pebbles. Apparently a highland of this series including Middle Devonian sediments existed to the north from which streams flowed with sufficient force to carry pebbles up to 4 inches in length and to form a deltaic type of deposit in Pennsylvanian time in northeastern Ohio.

SOLUBILITY AND RATE OF SOLUTION OF CALCIUM CARBONATE

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The rate of solution of calcium carbonate is a key to the rate at which calcite can be replaced by other minerals. A study has been made of the influence of temperature, acidity, and salinity on the solubility of calcium carbonate, and of the effect of acidity and temperature on the rate of solution. A method has been developed for the calculation of solubility at ionic strengths up to 0.7, over a wide range of pH, and over a temperature range from 25° to 65° C. Rate of solution has been determined empirically over a comparable temperature range, and over a pH range of 2 to 6. Correlation of the data shows approximately a fivefold increase in rate of solution at constant solubility with a temperature increase from 25° to 65° C., a doubling of the solution rate at constant temperature for each tenfold increase in solubility, and a tenfold increase in rate of solution with a pH change from 6 to 2 at constant temperature. All experimental rates were determined in open containers with slowly moving solutions.

SOME CHEMICAL AND MINERAL CHARACTERISTICS OF CARBONATE ROCKS DETERMINED FROM CHEMICAL ANALYSES*

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The accumulation of a large number of analyses of carbonate rocks from sampling programs in Bucks and Berks counties, Pennsylvania, by the Pennsylvania Geological Survey has led to an interest in determining some chemical and calculated mineral characteristics of carbonate rock units. The five major constituents generally reported have been plotted on three ternary diagrams: $CaCO_3 - MgCO_3 - SiO_2 + R_2O_3$, (CMS); $CaCO_3 + MgCO_3 - SiO_2 - R_2O_3$, (CSR); and $SiO_2 - Al_2O_3 - Fe_2O_3$, (SAF). The calculated dolomite content of any analysis and the "dolomite index" or average per cent dolomite are determined from the CMS diagram. An "insoluble index" and the S/R ratio are determined from the CSR diagram. The SAF diagram represents a plot of the recalculation of these three constituents to 100 per cent compared with plots of clay-mineral analyses. Indices, ratios, and other characteristics have been determined for several carbonate formations. Preliminary compilations of analyses of rocks from Bucks and Berks counties and other sources indicate that these characteristics tend to show certain constant relationships for individual forma-

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tions but vary markedly in many cases for different formations. They should be useful in describing carbonate rocks and may contribute to regional stratigraphic and sedimentation studies.

STRUCTURE OF THE JUDITH MOUNTAINS, MONTANA*

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The Judith Mountains are a group of coalescing domes that rise about 2000 feet above the plains of central Montana. Sedimentary rocks ranging in age from Cambrian to Cretaceous were invaded by Tertiary alkalic igneous rocks including monzonites, tinguaites, and granite. The larger intrusive bodies, around which the sediments are domed, were classed as laccoliths by Weed and Pirsson. However, detailed study of internal structures and contact relationships indicates that nearly all of these bodies are stocks that have broken through the Precambrian basement and domed the sedimentary rocks above. Dikes and sills are abundant in places.

Trap-door faults, bysmaliths, or punch structures and various intermediate forms are of special interest. On Kelly Hill, a remarkable hexagonal fault block is hinged on one side and tilted like a trap door. On Pyramid Peak, a nearly circular stock has been punched upward and is surrounded by circular faults to form a bysmalith.

It is suggested that the trap-door fault represents an early stage in the formation of a bysmalith; intermittent upward pressure of the magma first domed the sediments, then opened the trap door, and finally punched up the solidified roof of the stock.

The mountains are bisected by a strong, irregular normal fault of general east trend and moderate to steep northward dip. Nearly all the productive gold deposits in the mountains are along or close to this fault, and it is believed that the fault served as a trunk channel along which the ore solutions rose from depth.

SEDIMENTARY VOLUMES IN THE GULF COASTAL PLAIN: GEOPHYSICAL ASPECTS

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The very extensive commercial geophysical surveys in the Gulf Coast can make some contributions to the problem of thicknesses and attitudes of the sediments. These contributions are less definite than will be expected by many.

Gravity surveys can contribute little. Calculations of depths of salt columns from salt-dome gravity anomalies are extremely ambiguous owing to theoretical limitations and lack of independent knowledge of density contrasts.

Magnetic surveys can, under favorable circumstances, give fairly definite indications of basement depths and hence of total thicknesses of sediments. Results of such calculations at several points are presented.

Reflection-seismograph surveys can give information on dips, changes in dip, and convergence of lithologic intervals, which may be between, beyond, and below similar information from deep wells. Examples of long cross sections from combinations of seismograph and subsurface data are presented.

Special reflection surveys over shallow salt domes have shown isolated deep reflections from which the total height of the salt column may be calculated on the assumption that the reflections come from the base of the salt. Scattered examples are presented.

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WISCONSIN DEGLACIATION OF WEST-CENTRAL OHIO

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Wisconsin drifts of two ages, possibly Tazewell and Cary, are defined in southwestern Ohio by soil profiles, buried thin weathered horizons, and buried forest litter. Readvance of the younger (Cary?) ice covered large areas of gravel with till, but the outermost moraine of this advance is a double-crested till and kame moraine 3 to 8 miles back from the limit of readvance. In the subsequent opening of the interlobate area between Scioto and Miami lobes in west-central Ohio the continuity of several crest lines in the moraine complex and the profiles of two levels of outwash which head in kames fringing both ice lobes outlines two successive retreatal positions of the ice lobes.

FORMATION TEMPERATURES OF SOUTHERN ILLINOIS BEDDED FLUORITE AS DETERMINED FROM FLUID INCLUSIONS*

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Fluid inclusions in fluorite crystals were studied principally to determine the range of temperature of formation of individual crystals. Measurements were made by heating specimens and recording temperatures at which vapor bubbles within the inclusions disappeared. Overall accuracy, excluding pressure corrections, was of the order of 2.5°C.

Some of the fluid inclusions are arranged in geometrically regular planes parallel to cube faces. These are apparently of primary origin. Others form bands along former fractures which approximately parallel the cleavage directions and which cut across each other and the primary planes alike. Historically such inclusions have been called "secondary" although "subsequent" is considered a more meaningful designation. Most of the primary inclusions are smoothly rounded and contain petroleum, whereas "subsequent" inclusions range from jagged to smooth in outline and contain principally a clear fluid.

From measurements on primary inclusions, temperatures at which the crystals grew generally ranged from 85° to 120°C., with a mean around 100°C. Commonly the indicated growth temperature increased slightly for some distance outward from the crystal center and then dropped off toward the exterior. Measurements on "subsequent" inclusions gave results as high as 185°C., generally higher than those shown by primary inclusions.,

Incomplete bulk analyses of the fluid from inclusions, probably mostly of the "subsequent" variety, show a preponderance of Ca, Na, and Cl ions and a total concentration of dissolved material amounting to 45,000 parts per million.

LATE TRIASSIC GASTROPOD FAUNAS FROM CENTRAL PERU

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Study of rich gastropod faunas from various localities in the region of Cerro de Pasco and from one near Tilarnioc, in the Andes of Central Peru, revealed the presence of about 25 families with about 60 genera and subgenera, some of them new; more than 150 species, most of them new, are represented.

Close affinities, in some cases even conspecifity, with forms from the European Alps would suggest early Upper, or even late Middle Triassic age, were it not for the presence of genera hitherto

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believed to appear in the Liassic only or even later in the Jurassic. They are best known from France but sporadically they have been previously recorded, although not correctly identified, in the classical alpine Triassic faunas also. Thus, the richest and most characteristic lots, collected from a purely calcareous facies, might be dated as Norian or Rhaetian. This assumption is supported by the presence of the genus *Guidonia*, hitherto best known from the Norian of the Alps and of Italy, and perhaps also by that of the genus *Protofusus*, first described from the "horizonte calcáreo-dolomítico" of northwestern Argentina, whose age is controversial but most probably late Triassic. Other lots, collected from different facies, may be somewhat older, but are probably still Upper Triassic.

A hitherto unstudied fauna from Idaho, also believed to be of late Triassic age, has some characteristic genera and subgenera in common with the Peruvian one, but otherwise its composition is quite different.

TREATMENT OF CHALK FOUNDATION WITH BENTONITE SEAMS, HARLAN COUNTY DAM, NEBRASKA

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The modified gravity-type concrete spillway for Harlan County Dam, on Republican River in southern Nebraska, rests on Cretaceous Niobrara chalk with many interbedded bentonite seams up to 3 inches in thickness, and generally continuous throughout the foundation area. There is a general upstream dip of about 2 per cent, but varying from practically horizontal to at least 7 per cent locally near several normal faults of 10 to 25 feet displacement. The faults cross the site diagonally so that most of the spillway rests on a structural horst. Low specific weight and low elastic modulus of the chalk, and weakness of the bentonite seams, introduce problems in providing against downstream sliding or shearing in the foundation. Tests on samples show that first-cycle loading compresses the chalk more than similar loads applied in subsequent cycles, presumably indicating compensation for expansion following construction excavation, removal of drill-core samples from the foundation, or erosion of overlying geologic formations; and, supported by a field shear test after uncovering the foundation, show that the bentonite-chalk contacts are weaker than the bentonite itself.

Foundation treatment includes (1) steel anchor rods grouted inside 6-inch drill holes, inclined upstream on 2:1 slope, to tie together the chalk layers under the stilling basin and thus mobilize a greater mass to resist downstream thrust; (2) grouting of faults along the upstream side of the spillway; and (3) deep drain holes but no grouting in the chalk under the spillway. Both (2) and (3) are designed to reduce underseepage and uplift pressure.

SOME IMPLICATIONS OF THE GEOMETRY OF GEOSYNCLINES

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This paper expresses the possibility of determining the mechanics of geosynclinal phenomena through an examination of the changes in the geometry of these units as evidenced in the stratigraphic horizons. At this preliminary stage of investigation concepts are formulated as questions rather than as laws and conclusions.

The range of ratios between depth amplitude and geographical width for some North American geosynclines is established. Can these ratios imply the shapes and basement profiles of similar less-known structures? Theoretical directions of particle movement during a sinking phase of geosyncline history are developed. A suggestion of compatibility with the tectonic features of the Gulf Coast Geosyncline is evident. It is demonstrated that Appalachian type folding should not occur during a

continuation of this process unless the depth-width ratio is changed to such a degree that the cross-section area passes from an increasing to a decreasing value. In this case the directions of some of the particle movements are reversed. The question is raised whether any depth-to-width ratio of this magnitude is found in nature.

The suggestion is made that serious consideration be given to the possibility that both Appalachian type folding and some types of regional metamorphism may be the result of isostatic uplift of the geosynclinal unit between two massifs. The theoretical directions of particle movement during such a deformation are shown to be compatible with some recent observations in the Southern Appalachians.

SYNTHESIS OF FLUORINE MICAS AND RELATED LAYER STRUCTURE COMPOUNDS

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The synthesis of F-micas and related layer structure compounds has progressed far enough to furnish much information on the stability field of these important rock-forming minerals. However, much remains to be done.

Techniques of synthesis used in these investigations involve (1) fusion and crystallization, or (2) solid-state reaction. Many compounds such as F-muscovite can be formed only by the latter method. Special techniques often are needed to produce the desired reaction, especially at temperatures below 700°C. Examples of special techniques include the preparation and use of highly reactive batch materials, and the use of special atmospheres. Additionally, the proper choice of batch materials often is vital in obtaining the desired reaction product because in many cases, if not most, equilibrium conditions are not attained during the experiment.

Compounds synthesized include more than 100 different varieties of F-micas. Most of those related to the F-phlogopite subfamily can be crystallized from a melt; however, a few may be formed only by solid-state reaction. A few of the F-phlogopites melt congruently, but most of them dissociate below the melting temperature. All members of the F-muscovite and related lithium micas melt incongruently and can be formed only by solid-state reaction. The synthesis of F-talc and F-pyrophyllite has not yet been achieved although an interesting F-pyrophyllite has been made. A compound which seems to be closely related to the natural clay mineral, hectorite, has been prepared from dry melts.

PERMUTATIONS OF FUSULINIDS FROM THE MORAN FORMATION OF TEXAS

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About 300 fusulinid specimens from a single locality of the Moran formation (now placed at the base of Permian) 3 miles west of Dothan, Texas, were arranged according to the ratio of width to length, and then sectioned. Septa in some are highly fluted, but these grade into others with less-fluted septa and with general aspect of *Schwagerina* (in old sense). Sections of 105 specimens in the first group and 134 in the second were photographed, and their study reveals nearly continued intergradation from one extreme with most-fluted septum to the other with the least-fluted and most *Schwagerina*-like.

Sectioning of additional specimens revealed presence of more gradational forms filling some of the previous gaps in the grading series, while remaining gaps seem likely to be closed by sectioning of more specimens. The data of measures and counts, as standardized in modern fusulinid research, are tabulated leaving for the reader to make own taxonomic conclusions.

GEOLOGY OF THE CROOKED CREEK STRUCTURE, CRAWFORD COUNTY, MISSOURI

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The Crooked Creek dome is a cryptovolcanic structure located high on the northwest side of the Ozark Plateau in Crawford County, Missouri. Cambro-Ordovician formations involved in the structure are nonconformably overlain by lower Pennsylvanian sediments.

The central element of the structure is a roughly circular uplift, approximately 9000 feet in diameter, with a depressed apical area which creates a ring anticline, the axial trace of which delimits a shallow basin. The outer limbs of the ring anticline dip steeply outward and end against the upthrown sides of a series of peripheral, high-angle, normal faults. The Cambrian formations exposed in the shallow basin are intensely shattered, and in two small areas shatter cones are well developed. The Bonneterre and Davis formations exposed along the axial portion of the ring anticline are approximately 1000 feet above their normal level. The central uplift is surrounded by a ring-shaped graben, approximately a mile wide, in which the Ordovician formations are approximately 150 feet below their normal level. Outside the graben area, the country rock is disturbed only by the Palmer fault.

No high-temperature minerals or other evidence of hydrothermal activity were found. Magnetic surveys do not disclose significant anomalies.

The possible modes of origin are: (1) either salt or igneous intrusion; (2) subterranean explosion of gas and/or steam; or (3) meteorite impact and explosion. The first two possibilities are not supported by field evidence. The third possibility is not discredited by available field data.

CROSS SECTION THROUGH THE MARYLAND PIEDMONT OBTAINED FROM THE BALTIMORE-PATAPSCO AQUEDUCT

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The recently completed Baltimore-Patapsco aqueduct passed through 17 miles of Maryland crystalline rocks including, from west to east, 32,000 feet of Wissahickon schist, 36,400 feet of Baltimore gabbro, 4300 feet of quartz diorite and granite, 12,640 feet of Wissahickon schist and gneiss, 360 feet of Cockeysville marble, 600 feet of Setters quartzite, and 1990 feet of Baltimore gneiss.

In the first 15,000 feet of the Wissahickon schist, 46 previously unnoted intrusions of granite, aplite, and alaskite were discovered, ranging from 6 inches to 15 feet with the average just under 4 feet; all always in the *ac* plane. In the next 15,000 feet, *ac* faults are common; intrusions rarer except in *ab*. The schist itself reveals no systematic change, but is entirely oligoclase facies. A garnet is definitely developed as a result of the gabbro intrusion.

The Baltimore gabbro consists of two distinct intrusions: a more conformable ultramagnesian one and a later gabbroic one that intruded the ultramagnesics and the schist. Initial alteration in the ultramagnesics lead to an amphibolite; later alteration developed chlorite and talc. Serpentine probably also developed under these later conditions. A general funnel shape to the intrusion with the northwest side steeper than the south and east was confirmed.

Much of the quartz diorite consists of amphibolite and altered gabbro, and is only slightly disconformable to the gabbro; the granite more highly so.

The next formation was seen to be a highly injected Wissahickon schist rather than Baltimore gneiss as previously mapped. True thicknesses for the Setters quartzite and Cockeysville marble are 520 feet and 295 feet, respectively, indicating a considerable thinning from measured sections to the north.

PROBLEM OF DECOMPOSED DIKES AND HYDROTHERMALLY ALTERED JOINTS AT PINE FLAT DAM, CALIFORNIA

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The problem of decomposed dikes and hydrothermally altered joints in the amphibolite foundation rock at Pine Flat Dam, Kings River, California, and their significance in the design of the dam and the preparation of the foundation is discussed. Treatment of the dikes will probably consist of dental work. The dikes will be excavated to whatever depth may be necessary and backfilled with concrete. No treatment is planned for the altered joints below final foundation grade, but excavation will be carried to greater depths than otherwise in areas where they are prominent. The purpose of the dental work is to eliminate possibilities of differential settlement and of channeling along the dikes. Drains will be provided across the dikes to prevent the development of hydrostatic uplift behind the dikes. The presence of dikes and joints in the bedrock below the dam influenced the design of the spillway bucket.

ADSORPTION OF RADIOELEMENTS ON OCEAN-BOTTOM SEDIMENTS

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A kinetic theory of adsorption has been developed and has been tested on the removal of alpha-active radioelements by ocean-bottom sediments at extreme dilution in sea water. A new type of scintillation counter for determining the alpha activity of liquids has been used in this study. The number of available adsorption sites on sediments for heavy ions at various concentrations has been determined. The bearing of this data on the removal of the radioelements from the oceans during the settling of sediments is discussed.

EFFECT OF THE UNCOMPAHGRE UPLIFT ON THE MESOZOIC SEDIMENTARY ROCKS OF WESTERN COLORADO*

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The Uncompahgre Uplift, a positive Precambrian element of the Ancestral Rockies, was active during late Paleozoic. Its axis is near Gunnison, Colorado; near the Book Cliffs it plunges northwest and to the southeast it is buried beneath Tertiary volcanic rocks.

Subsequent movements along the uplift followed the late Paleozoic trend lines. Studies of detailed sections of Mesozoic rocks from the Front Ranges to Utah have revealed new data on the paleogeography.

The Triassic Chinle formation, 600 feet thick at the Utah line, thins progressively eastward and disappears near the Black Canyon of the Gunnison, reappears east of the uplift, and thickens to 600 feet near Aspen, Colorado. The Dolores formation, the Chinle equivalent in southwestern Colorado, likewise thins eastward from about 600 feet near Dolores to 20 feet in the Upper Piedra area. The successive formations in the Glen Canyon group disappear farther west. The Entrada sandstone, which rests on the Precambrian at the Black Canyon, where it pinches out, also reappears in the Colorado central basin. In a later stage, probably equivalent to the Curtis of northwestern Colorado, a basin characterized by gypsiferous deposits paralleled the western edge of the uplift; the Pony Express limestone, Bilk Creek sandstone, and Wanakah marl are confined to this basin. The Morrison is the first Jurassic formation to remain over the crest of the uplift, where it is less than 300 feet thick

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compared with a thickness of over 800 feet in the Nucla Basin. The Cretaceous formations were deposited over the crest and show little effect of the uplift.

CORRELATION OF EROSION SURFACES ON THE WEST FLANK OF THE WIND RIVER MOUNTAINS, WYOMING

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Composite longitudinal and cross profiles derived from topographic maps and field measurements indicate that only two major surfaces exist on the west flank of the Wind River Mountains. The Fremont surface (Westgate and Branson, 1913; Blackwelder, 1915; Baker, 1946), well developed in the Fremont quadrangle and truncating Precambrian granites and gneisses as well as folded Paleozoic sediments (Baker, 1946), continues southeastward with no abrupt change in level to 3 miles north of Big Sandy Opening. On the west, the Fremont surface is abruptly terminated by a steep escarpment and is transected by numerous deep canyons, which, like the escarpment, are possibly of tectonic origin (Richmond, 1945; Baker, 1946). The second major surface, Plain Number Three (Westgate and Branson, 1913) can be traced from near Big Sandy Opening to South Pass. The break between the two surfaces, north of Big Sandy Opening, is marked by relief of approximately 800 feet, but is softened by the presence of two massive lateral moraines. Plain Number Three bevels Precambrian granites, gneisses, and schists near the axis of the range, but continues to the south and southwest across Cenozoic sediments composed of white and light-gray silt and sand. Along the upper reaches of the Sandy and Sweetwater drainage systems, the light-colored sediments are being removed to expose youthful valleys which were developed subsequent to the Fremont cycle but before the deposition of the silt and sand.

FROST ACTION AND VEGETATION PATTERNS ON SEWARD PENINSULA, ALASKA*

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Frost scars, peat rings, tussock rings and groups, and tussock—birch—heath polygons in the Imuruk Lake area, Seward Peninsula, Alaska, are products of the interaction of congeliturbation and vegetation development. These cryopedologic features are found on poorly drained summit areas, slopes of less than 10°, and lowlands where silty mineral soil is present beneath peat or turf less than 3 feet thick. Perennially frozen ground is present at depth of 3 feet or less.

Frost scars consist of areas of bare soil resulting from disruption of the vegetation cover by local, intense frost heaving. Peat rings, tussock rings, and tussock groups are vegetation patterns associated with widely spaced mounds of mineral soil projecting through otherwise continuous layers of peat or turf. Tussock—birch—heath polygons consist of closely spaced mounds of soil separated by channels filled with peat. The peat rings, tussock rings, tussock groups, and vegetation polygons represent stages in several developmental series, all of which start with frost scars as the initial form. Each type of feature is in equilibrium with its immediate physical environment and the type of vegetation contributing to its formation.

Evidence of tussock—birch—heath polygons may be recognized in northern United States and Europe. Such evidence would be an indication of former perennially frozen ground from which the depth of thaw could be inferred by the vertical dimensions of the polygons.

Recognition on aerial photographs of cryopedologic surface features assists in the interpretation of terrain conditions.

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INTERRELATIONS OF GEOMORPHOLOGY, GLACIAL GEOLOGY, AND PLEISTOCENE GEOLOGY

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These fields of investigation are intimately interrelated and overlap in so many areas that sharp boundaries cannot be drawn. The preglacial topography is a primary factor in glacial interpretations, and glacial landforms as such constitute a major division of Geomorphology. From the Earth History point of view, Geomorphology and Pleistocene geology in most cases are synonymous. Most landscapes are complex and can be interpreted only in the light of climatic fluctuations, sea-level changes, and diastrophic events that occurred mainly during the Pleistocene.

ORIGIN OF GRANOPHYRE IN DIABASE IN SOUTHEASTERN PENNSYLVANIA*

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Small bodies of granophyre occur in the upper part of Triassic diabase intrusions in southeastern Pennsylvania. Near Harrisburg granophyre in the upper part of a diabase sheet was penetrated in a diamond-drill hole. Drill-core specimens show a gradational sequence from diabase to granophyre.

New data include 10 new chemical analyses and the results of petrographic study of a series of specimens from the drill core. The sequence, from diabase to granophyre, shows progressive increase in alkalies and silica; iron increases into transitional granophyric diabase, then decreases in the granophyre. The chemical variations are accompanied by changes in mineralogy.

It is concluded that crystal differentiation in a large sheetlike intrusion most satisfactorily explains the genesis of granophyre in this region. Prior to complete solidification, a residual liquid rich in iron, alkalies, silica, and volatiles accumulated locally in the upper part of the diabase sheet. In some places volatile-rich iron-bearing solutions that carried magnetite escaped into the overlying sedimentary rocks; the remaining liquid crystallized to fine-grained granophyre.

CENOZOIC AND MESOZOIC IN THE TEXAS PORTION OF THE GULF COAST

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Generalized isopach maps have been prepared for subdivisions of the Cenozoic and Mesozoic in the Texas portion of the Gulf Coast. In different formations along certain belts sudden thickening is evident, and in most cases the subsurface control downdip from these belts does not permit determination as to whether this thickening is local, or is increasing seaward, so that extrapolation of these thicknesses is highly speculative. Using only the maximum observed thicknesses in the different formations, and adding these together, the total sediments at the coast line of the Mesozoic and Cenozoic will be of the order of 40,000 feet.

The much more limited data concerning offshore thickness of the younger Cenozoic are also briefly discussed.

GEOMORPHOLOGY OF ANTARCTICA: A SUMMATION*

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The Antarctic Continent is pear-shaped, with Palmer Peninsula forming the stem. The western of the two indentations that form the waist of the pear is occupied by the Ross Sea, the eastern by

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the Weddell Sea. The Pacific sector is the area above the waist; the Polar sector is below. The continent is encased in ice that rises inland to elevations of more than 10,000 feet. The presence of several "highs" suggests multiple dispersal centers. Mountains appear only around the margins of the ice cap.

The Pacific sector consists of deformed rocks. In Palmer Peninsula accordant summits suggest a high-level degradational surface. The Polar sector consists of essentially horizontal sedimentary rocks resting on a Precambrian complex. Whether the accordant summits in this sector represent a depositional or degradational surface is unknown. The greatest mountain range in the Polar sector is carved from a horst 1500 miles long and more than 100 miles wide. Volcanoes are associated with the horst faults.

The Ross Shelf Ice, which is more than 1000 feet thick, mantles possibly 150,000 square miles of the Ross Sea. The Shelf Ice probably originated through accumulation of snow on a webbing of sea ice and floating glacier tongues.

Submarine banks off the continent may represent moraines deposited when the ice was more extensive than now.

MONOCHROMATOR UTILIZING THE ROTARY POWER OF QUARTZ

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The Emmons method of double variation for the determination of refractive index would be used more extensively if a more adequate light source were available. It is believed that this instrument meets the need.

The instrument utilizes the dispersion produced by the rotary power of quartz to obtain essentially monochromatic light. Four basal sections of quartz are used. Number 1 is of left-hand quartz 60 millimeters thick. Numbers 2, 3, and 4 are of right-hand quartz 30, 15, and 7.5 millimeters thick respectively. The sections are arranged so that a collimated and polarized light beam will pass through section 1 into section 2, 2 into 3, and 3 into 4. The light on emerging from section 1 passes through a polaroid plate, which eliminates nine bands equally spaced through the visible spectrum but permits nine others to pass into section 2. As the light emerges successively from each of the sections, it passes through polaroid discs which eliminate half of the number of bands that entered. When it has passed through section 4 and its polaroid, all but one band with an average width of 150 Å has been effectively eliminated.

By rotating simultaneously all four of the quartz sections with their attached polaroid, it is possible to change continuously the position of the single pass band so that it will move completely through the visible spectrum.

Because of the large aperture of the instrument, adequate light of all wave lengths can be obtained by using a tungsten filament lamp as a light source.

NEW EVIDENCE ON THE NEW BRUNSWICK GEANTICLINE

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The direction of overlap within the Cambrian sedimentary rocks of Cape Breton Island, Nova Scotia, indicates that the sea in which the Cambrian sediments were deposited was transgressing onto a landmass which lay to the northwest. Facies changes within these rocks show that the sediments were carried into the sea from the northwest. These rocks contain trilobite faunas belonging to at least seven of the standard faunal zones of the so-called Atlantic faunal realm. The author concludes that in this area, at least, the sea in which these rocks were deposited was separated from the contemporaneous sea in the St. Lawrence Valley by an intervening landmass, the New Brunswick Geanticline, rather than by a seaway or a facies barrier. This geanticline prevented the mingling of the Cambrian faunas of the Atlantic area with those of the interior seaways.

GROWTH OF CRYSTALS OF MICA AND RELATED FLUOSILICATES

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It is well known that fluorine may be substituted, in whole or in part, for hydroxyl in many crystalline silicates and chemically related compounds without essential structural changes. The structural and compositional limitations to such substitutions are considered with particular respect to bonding and to geometrical configuration. Possibilities of synthesis of such fluorine-substituted minerals as mica amphibole, chrysotile, topaz, apatite, and clay minerals are reviewed. Some principles are stated regarding the control of orientation in synthesis of platy and fibrous fluorine minerals by temperature gradients and other methods.

CHAOTIC BRECCIAS IN SOUTHERN CALIFORNIA: TECTONIC OR SEDIMENTARY?

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Tabular to lenticular masses of unusual breccias are widespread in both desert and coastal regions of Southern California. Some of the breccias are essentially monolithologic, and others are lithologically heterogeneous. Constituent rock fragments are commonly less than a foot across, although a few exceed small houses in size. Rocks commonly represented include limestone, dolomite, gabbro, anorthosite, diorite, quartzite, schists, gneisses, granitic and volcanic rocks, and magnetite-rich tactite.

Many of the breccias are sedimentary rocks, interlayered and intertongued with siltstones, sandstones, conglomerates, and tuffs. Typical examples occur in the Oligocene (?) sequence in the Ventura Basin, the Miocene in parts of the Coast Range province to the south, the Pliocene of the Avawatz Mountains, the mid-Tertiary of the Shadow Mountains, the Tertiary and Quaternary of the Panamint Range, and in other post-Cretaceous sections in the Mohave region. These breccias resemble modern mud-flow and debris-flow accumulations.

Some of the breccias, including several types that have been described as "chaos," have been interpreted as representing the crackled soles, tongues, or other parts of low-angle thrust faults, or as deposits of composite thrust fault-sedimentary origin.

Although certain breccias seem correctly interpreted as essentially tectonic in origin, others so interpreted are wholly sedimentary, with component fragments deposited a mile or more from their source. Both the number of low-angle thrust faults invoked in earlier studies, and the net slip inferred to explain the occurrence of breccias are exaggerated. Only further studies, however, can accurately define the respective roles of faulting and sedimentation in the development of these rocks.

ALPINE LEAD-ZINC ORES OF EUROPE

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The ore deposits of Cave di Predil (Raibl), Mezica (Miess), and Bleiberg-Kreuth, in Italy, Yugoslavia, and Austria, respectively, are representative of the Alpine lead-zinc ores of Europe and are of the "Mississippi Valley" type. In each case the upper 50–100 meters of the mid-Triassic (Wettersteín) limestone constitutes the chief ore horizon. The ore is in fissure veins and replacements, partly widely disseminated, and generally the bodies are not far below a relatively impervious covering formation (*e.g.*, the Carditas or Raibl slate). Overturned anticlines (Mezica) and especially tear faults controlled mineralization.

Besides the usual galena, sphalerite, marcasite, dolomite, and calcite mineralization, the ores contain fluorite, barite, chalcopyrite, and some arsenopyrite, together with noteworthy quantities of wurtzite. Wurtzite shows botryoidal, concentric bands, in part alternating rhythmically with marcasite and forming the so-called "Schalenblende" of German geologists. Much of this wurtzite is markedly anisotropic, in part converted to sphalerite but most stable where darker in color and richest in iron (Ehrenberg's theory). Where light yellow it was either first formed as sphalerite or has now inverted to that mineral. Disseminated zinc sulphide, however, was apparently sphalerite when first deposited, and a later, cross-cutting sphalerite can also be distinguished, though the possibility is not excluded that all the zinc sulphide was at first wurtzite. The darker bands of the "Schalenblende" may have derived their iron by primary resorption from the associated marcasite.

RELIEF WELLS FOR ARTESIAN SANDSTONE, FORT RANDALL DAM, MISSOURI RIVER, SOUTH DAKOTA

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Outlet works for Ft. Randall Dam rest on Niobrara chalk which in turn rests on the Carlile shale. The Codell sandstone, an artesian sandstone 20 feet thick and a member of the Carlile, is 30 feet below base of powerhouse structure. The Codell sandstone is continuous over large areas and an important source of water. Flow in Codell is from uplands toward Missouri River. During construction at a moderately high river stage, the hydrostatic pressure in the Codell would be considerably greater than the weight of bedrock. Conditions for completed project differ from construction period in that powerhouse excavation will be "backfilled" by structure, downstream area will have increased total weight due to structures and tailwater, however the pressure in Codell and upper Carlile will be influenced by reservoir pool as well as tailwater and will be higher than during construction period. Relief wells needed for pressure relief of completed project would be in way of construction activity; therefore it was necessary to install temporary pumped wells for construction period with permanent free-flowing wells to be installed when project is near completion. Temporary well system consisted of eight pumped wells spaced around periphery of excavation with drawdown to 1150 or a discharge of 200 gpm per well whichever was attained first. Wells produced considerably lower pressure under the outlet works than was actually anticipated. Permanent wells are now under construction. There will be approximately 35 free-flowing wells located around the periphery of the downstream outlet works. Spacing of wells for temporary system was determined by Electrical Analogy method.

STRUCTURAL SIGNIFICANCE OF LINEAMENTS

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Lineaments were first described 75 years ago, but they have received little attention since the work of W. H. Hobbs. Through the years, however, considerable literature has grown up, and several recent papers bear on the subject.

A lineament is a straight linear surface feature that is at least many hundreds of feet and commonly many miles long. Lineaments are well shown on aerial photographs and may consist of (1) linear topographic features, either trenches or ridges; (2) linear vegetation patterns; or (3) linear patterns of soil color or texture. Gaps and stream segments typically form parts of lineaments.

Lineaments observed by the writer are associated with zones of close-spaced random joints, with swarms of parallel joints, and with abrupt but minor changes in strike of sedimentary beds. The last feature seems to be deformation of a type quite different from either flexures or faults related to folding.

Those lineaments not directly related to faults or lithologic changes may reflect structures having

a common origin with echelon fault belts, trans-current fault zones, and related structures. The lineaments are thought to be passive structures produced by recurrent movement on basement blocks.

ORDOVICIAN CANADIAN-CHAZYAN RELATIONS IN VERMONT

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The Bridport dolomite formation along Lake Champlain is the uppermost part of the classic Beekmantown, the Canadian Series; the Beldens calcite marble of the Middlebury synclinorium, west-central Vermont, has been classed as upper Chazyan because it succeeds *Maclurites*-bearing beds, recently called Burchards, long thought to be middle Chazy Crown Point. The Bridport underlies quartz arenites and calcarenites of the basal Chazy Day Point formation within and west of Lake Champlain in Vermont and New York. The Beldens in the Middlebury synclinorium underlies Middlebury slaty argillicalcilutite; in the Highgate Springs sequence to the northwest, the Beldens is separated by succeeding Carman quartzite from Youngman slate in Vermont, and near St. Dominique, Quebec, the Beldens and Carman underlie calcarenites like those in the Day Point. The Beldens is interpreted as a calcitic facies of the Bridport dolomite, and of the upper Canadian Series; the two facies are continuous in outcrop in Cornwall and Shoreham, and each has interbeds of the dominant lithology of the other; the Weybridge quartz-silty facies of the Beldens in the Middlebury synclinorium has such genera as *Goniotelus* and *Syntrophia* in Orwell, Cornwall, and Weybridge, supporting late Canadian classification.

GEOLOGICAL SIGNIFICANCE OF VARIATIONS IN THE HIGH-LOW INVERSION OF QUARTZ

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Investigation of variations of the high-low inversion of quartz has been refined and extended to include almost 300 samples of synthetic and natural quartz from various sources.

The inversion temperature of samples of quartz grown in the laboratory under controlled conditions of pressure and chemical environment is in general an inverse function of the temperature of growth. That simple relationship is complicated, however, by the presence of an element such as germanium, which can substitute for silicon in the comparatively "tight" quartz structure, with profound effect on the inversion.

On the basis of temperature of inversion, natural quartz samples fall into fairly well defined groups which are clearly related to the conditions of origin. Quartz from rhyolites and related intrusive porphyries and welded tuffs inverts at temperatures clustered around 572.7°. Quartz from granites, with a few exceptions among those studied, inverts at higher temperatures clustered around 573.2°. "Granite" quartz and "rhyolite" quartz are completely separated on a plot of heating inversion versus cooling inversion. Most samples of vein quartz give high inversions, while samples of quartz from pegmatites show wide variations, even within one pegmatite mass. Details are presented regarding the inversion of quartz from zoned pegmatites and zoned crystals. Some suggestions are made as to the possible significance of the inversion characteristics of quartz from different types of granite.

ANALOGY BETWEEN DIFFUSION AND ELECTRICAL CONDUCTIVITY IN POROUS ROCKS

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Mass transfer in the diagenesis of sediments is accomplished by the movement of solutions, and by diffusion. In a recent paper Garrels *et al.* showed that the rate of transport is independent of the

permeability, but dependent upon an "effective directional porosity." Values of this parameter for several different rocks were determined by diffusion measurements. In view of the analogy which exists between diffusion and electrical conduction this result could have been predicated from electrical data, and the "effective directional porosity" is more easily determinable by electrical measurements.

In an open liquid-filled space the equations for diffusion and for electrical conduction, respectively, are:

$$g = -D_1 \text{ grad c},$$
$$i = -K_1 \text{ grad V},$$

where D_1 and K_1 are the diffusion constant and the electrical conductivity of the liquid.

In a rock composed of nonconductive minerals diffusion and electrical conduction will occur only in the pore space, and along sinuous paths. Hence in such a case the effective diffusion constant and electrical conductivity will be given by

$$D_r = \frac{D_1 f}{L},$$

$$K_r = \frac{K_1 f}{L},$$

where f is the porosity and L = a "lithologic factor" depending upon the sinuosity of the path. The geometrical factor f/L is the "effective directional porosity" of Garrels *et al.* It is the same for both electrical conduction and diffusion and can be determined much more easily by electrical than by diffusion measurements.

These deductions are confirmed by experiment, and several tables of data for rocks are presented.

TRAP-DOOR DOMES OF LITTLE ROCKY MOUNTAINS, MONTANA*

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The Little Rocky Mountains, a broad subcircular dome about 20 miles in average diameter, embraces more than 50 faulted subordinate domes that range in diameter from 1½ to 3½ miles. These subordinate domes were formed by upward pressure of alkalic igneous magma. They are typically subcircular or subelliptical in plan, and each includes a hinged block that was raised on a nearly vertical fault of curved trace. The faulted blocks were lifted like trap doors, and the rock strata within them dip generally toward the hinge. In some places the trap-door structure has been obscured by faulting within the tilted block. The faults within and at the margins of the trap-door blocks have throws that range from a few feet to several thousand feet; consequently the oldest rocks appearing at the surface in the blocks of different domes range in age from Precambrian to Upper Cretaceous.

Comments by Noble, Harder, and Slaughter (Geol. Soc. Am., Bull., vol. 60, p. 340, 1949) suggest that several of the domes in the northern Black Hills of South Dakota resemble those of the Little Rocky Mountains in a general way. Their descriptions do not, however, indicate that trap-door blocks are present in the domes of the northern Black Hills.

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CRETACEOUS BENTONITE BEDS OF MISSOURI RIVER BASIN AS SOURCES OF DRILLING AND FOUNDRY CLAY*

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Large quantities of commercial-grade bentonite for rotary well-drilling purposes are not known to be available for mining outside the Missouri River Basin, and at the present rate of depletion the small reserve of such material there available will presumably become exhausted within a few decades. Unless additional reserves or satisfactory substitutes are discovered in the meantime, it is anticipated that the lower grades of drilling bentonite will come widely into use, possibly through development of some economical beneficiating process.

Bentonite beds at many stratigraphic horizons in the marine Cretaceous rock formations of Montana, Wyoming, and South Dakota are believed to contain large resources of commercial-grade foundry sand-bonding bentonite and bentonite that can be used satisfactorily for drilling purposes. As drilling clay, however, only a small proportion of this material measures up to present commercial standards. Most of the minable reserve of drilling bentonite of commercial grade in the Missouri River Basin is apparently contained in the Mowry siliceous shale member of the Graneros shale (Upper Cretaceous). In the vicinity of the Black Hills both drilling and foundry clay have been strip-mined extensively from the Clay Spur bentonite bed, near the top of the Mowry shale. At numerous other places in Montana and Wyoming bentonite deposits several feet thick occurring at the stratigraphic horizon of the Clay Spur bed include material comparable in requisite physical properties with the high-grade drilling clay mined in the Black Hills district. In general these deposits are so situated in relation to geologic structure and topographic features as to offer few attractive mining sites.

PENNSYLVANIAN PLANT MICROFOSSILS AND PALEOECOLOGY†

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In a previous publication the small spore population of most of the Pennsylvanian coal beds of Illinois was determined. Changes occur in the small spore population from bottom to the top in a number of these coal beds. These changes are in the types of spores present, in the percentage of the spore population, or both. This variation in the spore population suggests a changing flora, indicating a succession of plants during the development of a coal bed. Changes sometimes occur in the percentage of spore populations of the same coal bed when the samples studied are from widely separated geographic areas.

These floristic changes afford an interesting study in paleoecology which might have a bearing upon the constitution of the coal. Small vertical segments of coal cores were studied to trace the plant succession beginning with the primary plant community as revealed by the examination of the basal millimeter of coal in direct contact with the underclay. Next, where widespread shale partings were present, as in the Herrin (No. 6) coal bed, a millimeter of coal immediately above and below these shale partings was examined to determine the type of vegetation present before the shale deposition and the re-entrant plant community. Finally, the top millimeter of coal in direct contact with the caprock was also examined to determine the type of plant community existing prior to cessation of plant deposition. Studies of the plant succession within the No. 5 and No. 2 coal beds is also discussed.

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STRONTIUM ISOTOPE AGE PROJECT—PROGRESS REPORT

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An attempt is being made to develop a method of estimating the age of carbonate rocks and shells by the Sr^{87}/Sr^{86}. The first phase of the work required the determination of the strontium content of such materials. Various fossil types have been analyzed (Ordovician through Cretaceous in age) giving a range of 0.02 to 0.30 per cent SrO with an average value of about 0.1 per cent SrO. Limestones and marbles which ranged from Precambrian to Cretaceous in age showed a somewhat lower range of 0.01 to 0.20 per cent with an average value of 0.08 per cent. These values indicate that it will be possible to separate enough strontium from most carbonate rocks and shells to make isotopic analyses.

STRATIGRAPHY OF THE DUNDAS HARBOUR AREA, DEVON ISLAND, ARCTIC ARCHIPELAGO*

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Cambrian and Ordovician sediments at least 3450 feet thick overlie Precambrian gneisses along the southern shore of Devon Island. The rocks have a very gentle northwest dip and are broken by a few minor high-angle normal faults.

The Lower Cambrian is represented by gray and red sandstones approximately 70 feet thick containing *Olenellus* and *Scolithus*. The Middle Cambrian consists of shales and dolomitic limestones approximately 1250 feet thick containing *Dolichometopsis*, *Glossopleura*, *Pachyaspis*, *Elrathia s.l.*, and *Micrometra*. Upper Cambrian rocks have not been recognized.

The Lower Ordovician strata are approximately 850 feet thick. They consist dominantly of limestones and in their lower part form strong limestone cliffs that can be traced at least as far west as Croker Bay. *Symphysurina*, *Hystricurus*, brachiopods, Porifera, gastropods, and cephalopods occur in the part of the section that tentatively is assigned to the Lower Ordovician.

Middle Ordovician rocks are at least 1280 feet thick. The lower part of the Middle Ordovician forms a set of three closely spaced cliffs. *Isotelus*, *Maclurites*, and *Receptaculites* occur in this part of the section. The highest zone containing *Maclurites* and *Receptaculites* is overlain by an unknown thickness of younger strata that have not been studied.

COMPARISON OF THE CYCLIC DEPOSITS OF THE CASTILE AND SALADO FORMATIONS OF THE PERMIAN OF THE SOUTHWEST†

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The deposits of the Castile and Salado formations of the Permian of the Southwest are more or less rhythmically layered. These layers formed during annual cycles of deposition, and their number represents approximately 500,000 years. The cyclic deposits of the Castile are more regular and persistent than those of the Salado, which are coarser, more variable, and in places difficult to define. These alternations in deposition, which are due to climatic variations during the year, form couplets or varves in both formations. The varves of the Castile formation are made up of minerals that

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belong to the early stage of mineral crystallization from sea water and include organic residues. The varves or cycles of the Salado include contributions interpreted to have come from the marginal land areas about the basin. These accessory inclusions are significant indicators. The organic layers of the Castile mark the base of a varve and represent the winter period. The mineral assemblages deposited in the summer and winter varves in the Castile formation are represented as follows:

$$\frac{\text{(summer)}}{\text{(winter)}}\ \frac{CCa}{CCa},\ \frac{Ca}{CCa},\ \frac{A}{CCa},\ \frac{A}{CA},\ \frac{A}{A},$$

in which C is carbon, Ca is calcite, and A is anhydrite. The series of cycles of the Salado formation is represented by the succession

$$\frac{A}{A},\ \frac{A}{M},\ \frac{A}{MG},\ \frac{H}{MG},\ \frac{H}{H},\ \frac{H}{S},$$

in which A is anhydrite; M, magnesite; G, gypsum; H, halite; and S, sylvite. A correct interpretation of these factors leads to a disclosure of the environmental conditions during deposition of these chemical deposits.

METHOD OF DETERMINING THE AGE OF IGNEOUS ROCKS USING THE ACCESSORY MINERALS*

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In the common igneous rocks most of the lead is concentrated in the potash minerals, and most of the radioactivity in the zircon and other accessory minerals. The lead in the potash minerals is believed to be mostly primary lead; that in the accessory minerals is probably chiefly radiogenic lead. By separating the accessory minerals of fresh igneous rocks, determining the lead with the spectrograph and the radioactivity by alpha counts, it was found that the age of the rocks could be determined with an error of approximately 10 per cent. Basalts and gabbros may carry too few accessory minerals for satisfactory age determination by this method. Zircon is the most satisfactory mineral for this kind of determination and can be used for rocks as young as Miocene. Apatite from young rocks is too low in lead for accurate age determination, and sphene seems to give somewhat erratic results. By using very young rocks (Miocene) it was found that very little primary lead crystallizes with the zircon and apatite.

STRATIGRAPHY OF THE PLATTIN LIMESTONE IN SOUTHEASTERN MISSOURI

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Several distinct lithologic units have been recognized in the Plattin limestone (Middle Ordovician) in southeastern Missouri. From older to younger they are:

1. oölitic and carbonate-pebble bearing calcilutite frequently with green shale layers and dolomite beds
2. fucoidal, fine-textured calcitite
3. fossiliferous, fine-textured calcitite, which grades northward into calcarenite and calcilutite
4. fucoidal calcitite and succeeding fossiliferous calcitite, the latter with shaly partings and a widespread metabentonite near the top.

Northward thinning of the Plattin from approximately 400 feet at Cape Girardeau to approxi-

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mately 125 feet in southern Lincoln County is by convergence within units and offlap-overlap of units. The lower fucoidal beds (unit 2) overlap unit 1. The lower fossiliferous calcitite (unit 3) disconformably offlaps unit 2 and is thick where the latter is thin. Unit 4 thins by reduction of the fucoidal portion; the upper fossiliferous beds are essentially platelike.

The Plattin has been classified as Bolarian (of Black River age) and correlated with the Platteville of the upper Mississippi valley. Faunules from the shale-bearing beds of unit 4 suggest that those beds are lower Trentonian. Lower beds are like the Bolarian in Central Kentucky.

STRATIGRAPHIC ZONATION OF THE PEORIA LOESS IN KANSAS

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The late Pleistocene Peoria loess, unconformable above the Loveland (Sangamon) fossil soil, is terminated above by the Brady fossil soil, which is overlain in many places by Bignell loess and Recent soil. The Peoria loess contains a distinctive molluscan fauna, which is distinguishable from the Loveland fauna and from the Bignell and Recent faunas in this region. Three zones are recognized in the Peoria loess: a basal zone devoid of mollusks, and a lower and an upper faunal zone characterized by different assemblages of mollusks. Each zone is readily recognizable in the field. Since the Peoria loess is younger than the Sangamon interglacial interval, and in the glaciated region is associated with the Iowan till, and since the upper zone fauna is correlatable with a Tazewellian molluscan fauna, the following interpretations are made: The basal zone is earliest Wisconsinan and is tentatively correlated with the Farmdale loess of central Illinois; the lower faunal zone is Iowan or late Iowan, the upper faunal zone Tazewellian in age, with the transitional faunal zone representing a time of climatic shift between Iowan and Tazewellian time. From the faunal evidence, Iowan (Rocky Mountain) glaciation accounts for loess deposition as far south as southwestern Kansas, northwestern Oklahoma, and northern Texas, while Tazewellian influence extends only into west-central Kansas. Available evidence is insufficient to assign the Bignell loess to either the Caryan or Mankatoan glaciations, though the time interval involved must represent both.

MAGNETITE DEPOSITS OF THE ST. LAWRENCE COUNTY DISTRICT, NEW YORK*

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Two nontitaniferous magnetite deposits of St. Lawrence County, northwestern New York, were reopened in 1941. Between 1941 and 1946, 10 promising new deposits and 12 small prospects were found, chiefly by systematic geophysical prospecting based on local and regional geologic studies.

The magnetite deposits are in old Precambrian rocks and belong to two geologic types—deposits in skarn and deposits in granite gneiss. Each of the types has been modified locally to form important subtypes. Skarn ores tend to be massive and are variable in grade, complex in structure, and small to moderate in size. They are strikingly similar to those found in central Sweden. Granite gneiss ores are disseminated deposits of uniformly low grade, remarkable continuity, and moderate to very large size. The disseminated magnetite is accompanied by primary crystalline hematite, quartz, potash feldspar, biotite, manganiferous garnet, and sillimanite. A modified type in granite gneiss has abundant spessartite and fluorite; barite is a prominent accessory.

The ore deposits are restricted to a complex structural knot of metasedimentary rocks and sheets of younger granite pressed into isoclinal folds against buttresses of older granitic rocks. The deposits are on the limbs or noses of folds, often appearing as fishhooks in plan. The ore is younger than the deformation and metamorphism of the host rocks. It formed as a high-temperature replacement

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effected by solutions derived from younger granite magma. Evidence of late hydrothermal leaching of the mineralized zones is noteworthy in several deposits.

Zoning of Adirondack mineral deposits is discussed.

ORIGIN OF HORNBLENDE RIMS ON ADIRONDACK GARNET

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Rims (shells) of coarse hornblende surround large garnet crystals in coarse metagabbro at the Barton garnet deposit and other occurrences of this type in the southeastern Adirondacks. It is concluded that the hornblende rims formed contemporaneously with the growth of the large garnets by a process of metamorphic redistribution of hornblende already present in the rock matrix. Each large garnet, as it grew by recrystallization from originally fine-grained, disseminated garnet, displaced matrix plagioclase and hornblende. Of these the plagioclase displayed considerable mobility and was redistributed in the matrix, but the displaced hornblende was less mobile and accumulated as a rim around the large garnet. This conclusion is based upon the nearly constant volumetric ratio of rim to garnet, the essential identity of rim and matrix hornblende, the volumetric equivalence of rim hornblende to calculated displaced hornblende, and the evidence of plagioclase mobility. Conversely, consideration of chemical composition and textural features argue against rim formation either by reaction or by retrograde destruction of the garnet.

PETROGRAPHY AS AN AID IN DATING TERTIARY VOLCANIC ROCKS*

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In connection with stratigraphic studies and mapping of Tertiary rocks in Wyoming during the last 15 years, about 500 rock samples have been collected, both from fossil-bearing beds and from beds whose age and stratigraphic relations could be determined by other means. Thin sections were cut from all specimens, and heavy-mineral separations were made from some.

Study of these specimens suggests a general correlation between ages and types of volcanic rocks throughout all parts of Wyoming where data are adequate. Although many exceptions can be found for each generalization, the pattern of rock types, when used with caution and with a sufficient number of representative samples, is useful in dating unfossiliferous pyroclastic rocks, and determining the structural history of areas. It is not known whether this pattern holds true in adjacent regions, but perhaps if it is called to the attention of others, they may broaden or delimit the following "petrographic calendar":

(1) Lower Eocene rocks: contain little volcanic material; but, where present, it is commonly hornblende andesite with plagioclase, hornblende, and biotite, deeply weathered.

(2) Middle Eocene rocks: contain hornblende andesitic and rhyolitic material, fresher and more abundant than in lower Eocene.

(3) Upper Eocene rocks: contain pyroxene andesitic material, characteristically green or olive drab.

(4) Oligocene rocks: contain hornblende andesitic material, with plagioclase, hornblende, and biotite fresher and with characteristics different from those in middle Eocene; rocks commonly white.

(5) Miocene rocks: contain pyroxene andesitic material, less weathered and distinct from upper Eocene; rocks characteristically have variety of bright-colored grains.

(6) Pliocene rocks: contain rhyolitic material; data less adequate than for older Tertiary rocks.

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SIGNIFICANCE OF RHYTHMIC SEDIMENTATION OF THE UPPER SILURIAN LIMESTONES OF WEST VIRGINIA

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The Tonoloway and the underlying Wills Creek limestones are of Cayugan age and are the uppermost definitely Silurian formations in West Virginia. The Cayugan Series in large part correlates with the Salina Group of New York. Many lithologic zones of the outcrops of these limestones in eastern West Virginia consist of chemically precipitated, alternately light and dark laminations which were rhythmically deposited under very quiet conditions. Couplets of the laminae appear to be homologous to varves in the sense that each lamina represents a pulse in the accumulation of the dark organic material on the bottom of shallow saline bodies of water. Salt-crystal impressions in zones in the limestone closely associated with the laminated zones indicate an equivalent time relationship to the great salt deposits of the Salina.

It is extremely unlikely that the laminated limestones could have been deposited over such a wide area in an environment of strong tides which must have characterized Silurian seas, and it is concluded that during extended periods of chemical precipitation at least this part of the Appalachian basin of deposition was not connected with the ocean. Associated zones of clastic deposits and zones of intraformational breccias formed from the laminated limestones may have been developed during periods when the sea barrier was below sea level. Support is thus indirectly given to bar or tidal-flood theories for the origin of thick rock salt deposits of the Salina.

STRUCTURE AND STRATIGRAPHY OF THE INDE-CIENEGUILLAS DISTRICT, DURANGO, MEXICO

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The district is situated in north-central Durango. As far as can be determined this report is the first comprehensive study of the area. Tentative stratigraphic correlation is offered, and formation names are proposed.

The stratigraphic section is believed to extend from Upper Paleozoic through the Quaternary and is outlined as follows:

Quaternary—Outwash gravels and sand

Tertiary—Basal limestone talus formation overlain by agglomerate and tuff and capped by andesitic flows

Lower Middle Cretaceous (Albian)—Thick series of interbedded coarse conglomerate and locally impure limestone

Lower Cretaceous (Neocomian-Aptian)—Thin-bedded limy shale with local discontinuous beds of limestone and sandstone

Jurassic—Interbedded conglomerate and agglomerate

Upper Paleozoic—Strongly crenulated phyllite

The structural history of the region is characterized by persistent crustal disturbance broken by periods of subsidence and erosion. Throughout the Mesozoic and Cenozoic the area was consistently deformed by southwest-northeast compressional forces.

The earliest recorded orogenesis came at the close of the Paleozoic era. Volcanic activity occurred during the Jurassic. A period of minor folding brought to a close the shallow-water sedimentation of Neocomian-Aptian time. Orogenesis continued during Albian time southwest of the district and culminated in overthrusting. The most recent disturbance was the development of a regional arch modified by block faulting which followed Tertiary igneous activity.

BYSTROMITE, MAGNESIUM ANTIMONATE, A NEW MINERAL

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Antimony ores from Antimonio, Sonora, Mexico, contain a new mineral corresponding in chemical composition and structure with magnesium antimonate, $MgSb_2O_6$, although in the mineral some of the oxygen is replaced by hydroxyl groups and the lattice is deficient in antimony. The mineral is massive, color light blue gray, streak white, density 5.4 ± 0.1; the only associated mineral is quartz. Tetragonal (ditetragonal dipyramidal), a = 4.68A, c = 9.21A, c/a = 1.968, space group P4/mnm; the structure is of the trirutile type, and the mineral is isomorphous with tapiolite ($FeTa_2O_6$) and with many artificial antimonates and tantalates. The name bystromite is proposed for the mineral after Anders Bystrom, Swedish crystal chemist, who worked out the structure of synthetic magnesium antimonate in 1941.

FURTHER ACCOUNT OF THE NATURALLY OCCURRING ANTIMONY OXIDES

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A survey of the literature shows that the alteration products of the ores of antimony are in general classified under one of the following names:

Cervantite—Sb_2O_4 or $Sb_2O_3 \cdot Sb_2O_5$—1854
Stibiconite—$H_2Sb_2O_6$ or $Sb_2O_4 \cdot H_2O$—1832
Hydroromeite—$(Sb^{+++}, Ca^{++})_2O(O_2, (OH)_2) \cdot 2Sb_2O_5$—1932

The study of over 50 specimens from widely scattered localities indicates that not all these names are valid. X-ray data show the existence of only one phase, which is sometimes admixed with valentinite, Sb_2O_3. By spectrographic analysis, this phase has a range in CaO up to 22 per cent. The phase is isometric, the dimension of the unit cell being 10.27 Å. The index of refraction ranges from 1.66 to 1.9 (+), the density ranges from 3.2 to 5.4, and the H_2O content ranges from 2 to 13 per cent. When the CaO content is low admixed valentinite is present, suggesting that calcium is an essential constituent of the phase.

The present work on the homogeneous phase indicates a formula corresponding to $(Ca, Sb^{III})_{0-2}(Sb^{V})_{2-X}(O, OH, H_2O)_{6-7}$ where X varies from 0. to 0.5.

MOUNT GARIBALDI, A "SUPRAGLACIAL" VOLCANO?

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Mount Garibaldi, in southern British Columbia, is a composite volcano built in large part by glowing avalanches accompanying an almost uninterrupted series of Peléean eruptions. Erratics on the lower slopes of the cone show that its present size was attained before the disappearance of the Cordilleran ice sheet, but the absence of erratics at the highest levels known to have been reached by the ice indicates that construction took place after the Wisconsin climax of the sheet. Several significant relations are noted: (1) undisturbed Peléean flows extend no farther from the vent down the major valleys than they do along near-by high ridges, (2) kettlelike depressions exist in the surface of the cone, (3) no sharp break exists between glacial till abundantly charged with fragments from Mount Garibaldi and underlying till free from this debris, and (4) a very marked contrast exists in the degree of dissection of different slopes; the west side has lost almost 1 cubic mile of debris mainly by Late Wisconsin mudslides, the south slope is preserved in almost its original form. All these features can be accounted for by the hypothesis that the volcano was built while Cordilleran ice still occupied the valleys and that parts of the cone were built on the ice surface.

CRYSTAL CHEMISTRY OF MONTMORILLONITE. II—CALCULATION OF THE STRUCTURAL FORMULA

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As a sequel to an earlier paper describing a new hypothetical structure for montmorillonite, a scheme for calculating the contents of the elementary cell is presented. The method of calculation assumes an integral number of large anions, (O + OH) = 24, and relegates the analytically determined cations (including hydrogen) to the basis of 48 charges in order to obtain the unit-cell contents. The assumptions involved in this method of calculation are discussed. The calculations are applied to a new analysis of highly purified montmorillonite for which water determinations are available between 305° and 760°C and above 760°C. The results are consistent with the hypothesis postulating the occurrence of hydroxyl ions in the tetrahedral layer of this clay mineral.

EARLY PLEISTOCENE FAUNA FROM FREDERICK, OKLAHOMA

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The Holloman gravel pit deposits at Frederick, Oklahoma, are located in a remnant of the highest terrace level of the Red River. An examination of fossil vertebrates recently acquired from this site and a re-examination of the fauna described by Oliver P. Hay and Harold J. Cook indicate that the significance of this fauna has not been fully appreciated.

The recently acquired small collection includes specimens of *Gigantocamelus* and a horse that is probably *Hippotigris*, neither of which has previously been reported from the site. *Stegomastodon*, reported by Hay and Cook, is also represented in the new collection. These three genera are short-range fossils characteristic of the Blanco (Nebraskan) and correlatives.

Kansan age faunas are characterized in part by the presence of the mammoth and *Equus* and by the absence of these characteristic Blanco genera. The Holloman site is significant in that here is the first occurrence of the mammoth and *Equus* in association with the typical early Pleistocene genera *Gigantocamelus*, *Stegomastodon*, and *Hippotigris*. This association probably indicates a fauna of Aftonian age.

CHUBB CRATER, UNGAVA, QUEBEC

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A crater, approximately 2 miles in diameter and with a rim rising from 300 to 500 feet above the surrounding plain, has been discovered west of Ungava Bay in the Province of Quebec. The depth of the crater is unknown since a lake covered with floating ice occupied it at the time of the investigation. The native rock is a granite gneiss, and there is no sign of vulcanism. Three sets of fractures—radial, tangential and about 15° outwards—observed at all parts of the rim indicate that the crater was caused by a great explosion. Ridges in the granite gneiss in the near-by plain appear to be circular compression ripples surrounding the crater. Great troughs through the rim may be similar to the radial markings shown in the craters on the moon. Although no fragments of meteoritic material were recovered, it is believed that this crater is of meteoritic origin. The date of the fall is tentatively placed near the end of the last ice age.

TECTONICS AND THE DAVIS ASSUMPTIONS

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The physiographic concepts most fully developed by William Morris Davis were qualitative rather than quantitative, and many of his followers seem to be convinced that a pair of eyes is the

only basic equipment geomorphologists need. A recent study by Olmsted and Olmsted reveals severe physical limitations in visual analysis of landforms, and points the need for mathematical and statistical analysis such as were introduced into the literature by Horton. Modern methods drawn from mathematics, physics, and engineering, when applied to stream gradients, erosion surfaces, and slopes show that regional geomorphic features are composite in form, hence composite in origin. Differential rock hardness is the usual explanation offered, whether or not it applies, and whether or not available stratigraphic sections record a series of diastrophic movements that must be reflected in the erosional landforms of adjacent uplands. Quantitative studies prove that such basic Davis assumptions as prolonged stillstands of land and sea, and prolonged preservation of exposed erosion surfaces, must be abandoned in favor of a concept involving numerous minor changes in sea level, punctuated at longer intervals by major diastrophic movements. Whether major or minor, each change leaves its impression on the subaerial landforms produced. These impressions vary in importance with the length of the time interval between changes and the antiquity of each change.

IMMERSION LIQUIDS OF HIGH REFRACTIVE INDEX*

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A study of inorganic, organic, and metal-organic compounds that might be employed in the preparation of high refractive index liquids has been undertaken.

Mixtures of arsenic tribromide and precipitated sulfur yielded a series of clear yellow liquids (mixture A), stable at room temperature. An index of 1.829 was obtained. After a period of 12 weeks, the maximum change in index was 0.003. The mixing curve of mixture A with methylene iodide (n = 1.74 to 1.81) deviated considerably from a straight line.

At room temperature, mixture A and arsenic disulfide formed a series of clear green-yellow to green-amber liquids (B) whose indices range from 1.876 to 1.952. The maximum change in index after a period of 12 weeks was 0.004 for those liquids below 1.92 and 0.007 for those above 1.92. When the temperature was raised during preparation, liquid B was obtained with n = 2.006. The mixing curve of A and B is a straight line (n = 1.81 to 2.01).

Red mercuric sulfide added to mixture B gave a clear yellow and very viscous liquid whose index was 2.035.

Black selenium added to mixture B gave a clear, light-red semiviscous liquid whose index was 2.017.

Arsenic tribromide, arsenic disulfide, and black selenium formed a very dark-red, viscous liquid whose index was 2.008.

All the liquids described give an acid reaction and decompose some minerals.

GEOLOGY OF THE BRANFORD-KILLINGWORTH AREA, CONNECTICUT†

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In the southwestern corner of Connecticut's Eastern Highland section the dominant structural and petrologic features are two stocklike massifs of granite and quartz monzonite and an older and larger pluton of biotite tonalite. The tonalite pluton contains gradational concentric changes in fabric from hypidiomorphic-granular to allotriomorphic-gneissic and compositional changes of the plagioclase and hornblende content. The three bodies contain flowage features which describe domal

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structures. These structures parallel the peripheral contacts, although a zone of mixed rocks is present in the outer part of each intrusive.

The pre-Triassic Middletown and Bolton formations, into which the plutons intruded, are principally metasedimentary rocks. The former is marked by the presence of hornblende and comprises various gneisses formed from interlayered basaltic tuff and pelitic-psammitic sediments. The Bolton formation lies stratigraphically above the Middletown gneiss and consists of schists and quartzites. Contact between the two formations is conformable. Foliation and layering in both are parallel. Both formations contain much pegmatitie in bodies ranging from tiny stringers to hundred-foot lenses.

The northwest corner of the area investigated is underlain by sediments and two lava flows of the Triassic Newark group. The eastern border fault, which separates this group from the crystalline rocks, is exposed at one place where a westward dip of approximately 55° was measured. Oblique faults within the Triassic Lowland area and dip abnormalities, including "reverse drag" and half-basin folds in the Newark beds, are discussed.

LATE CENOZOIC DIASTROPHISM IN HIMALAYAN SYSTEM

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In interior Northwest Himalayas north of Nanga Parbat, Indus gorge coincides with steep syncline of Pliocene or early Pleistocene arkoses, parallel to tectonic line in crystalline substratum Pleistocene terraces truncate syncline. Lack of locally derived coarase materials, and derivation of basal gravel from rocks exposed 150 miles upstream, indicate deposition of arkoses in broad flat Indus depression contrasted to present steep topography with maximum relief of 23,000 feet. Nanga Parbat massif south of syncline rises thousands of feet above surrounding ranges. Synclinal folding along Indus suggests simultaneous uplift of massif. Powerful late Cenozoic differential uplift is confirmed by remnants of mature surfaces at various high levels. Differential movements were combined with, and followed by, further strong overall uplift, as indicated by extreme general rejuvenation. Late Cenozoic diastrophism at other localities in interior Himalayas and along foothill zone is discussed.

Southeastern prolongation of interior Himalayan zones in Northwest Yunnan exhibits similar history of powerful late Cenozoic differential uplift, but of block type. On late Tertiary surface of moderate relief, local lake basins formed during Pliocene. Basin and Range block faulting followed, exceptionally with some folding. Relative uplift of some blocks exceeded 10,000 feet. Strongest faulting was pre-glacial, but lesser movements continued. Differential movements were combined with and followed by further strong overall uplift. Absolute movement of both basins and ranges was upward. Overall uplift caused general rejuvenation seen in gorges of major rivers and lower courses of tributaries, which are several thousand feet below levels of uplifted Pliocene basins. Differential movements caused local rejuvenations, with uplifted basins as base levels. Upper Yangtse-kiang, deflected to north before diastrophism, cut antecedent gorge about 15,000 feet deep across highest block.

GEOLOGY AND FOUNDATION TREATMENT OF SOUTH HOLSTON DAM, TENNESSEE

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South Holston Dam, built by the Tennessee Valley Authority, is located on South Fork Holston River at Mile 49.8, in Sullivan County, Tennessee.

The main dam is a combination earth and rock structure which has a maximum height of 285 feet and a maximum length of 1550 feet. It is founded entirely upon the Tellico formation (Ordovician) which consists of alternating layers of sandstone and shale. The strike of the strata in the foundation is N 45° E, approximately normal to the axis of the dam, and the dip is 10° to 45° to the southeast. The only geologic problems involved in the preparation and remedial treatment of the foundation were occasioned by weathered shale.

An auxiliary dam was constructed across Holston Valley 11 miles upstream from the main dam. This structure is nearly normal to the Valley and is founded on limestone and dolomite of the Knox dolomite. The structure of the valley is anticlinal, but the main anticline is complicated by numerous minor folds and thrust faults. The deeply cavernous character of the rock necessitated an intensive foundation-treatment program. More than a million cubic feet of clay-cement grout was used in making the foundation watertight.

SOLUBILITY OF QUARTZ AND SOME OTHER SUBSTANCES IN SUPERHEATED STEAM AT HIGH PRESSURES

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This paper is a summary of several studies in each of which the solubility of a solid in superheated steam was determined. The results are at 400° and 500°C, and at pressures ranging from 1000 to 30,000 psi. One series of gases are those in equilibrium with liquids at the saturation surfaces in the system H_2O-Na_2O-SiO_2. Other results are in two-phase systems, gas plus solid, in which the solids include quartz, NaCl, Li_2SO_4, Na_2SO_4,K_2SO_4, $CaSO_4$, Fe_2O_3 and some sulfides.

SUPERGENE AND HYDROTHERMAL DISPERSION OF HEAVY METALS IN WALL ROCKS NEAR ORE BODIES, TINTIC DISTRICT, UTAH*

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PART I

Mobility of Heavy Metals in Ground Water

T. S. Lovering.

Preliminary work determined the relative distance of migration of ore metals in moist carbonate and quartz wall rocks near ore, and in ground water having a very sluggish circulation through mineralized ground. The analyses of efflorescences in the Tintic Standard mine openings at suitable localities indicated that under the conditions existing during the past 25 years lead has not moved perceptibly; gold has migrated only a few inches; copper has moved a few score feet at most, and only in acid solutions; and zinc has traveled hundreds of feet but not as far as some silver. The migration of silver may be arrested by contact with sulfides, but in the oxidized zone it travels far in detectable amounts.

The distance traveled in solution is determined by the pH of hydrolysis of the metal, the solubility of sulfates of the metals, and the position of the metals in Schürmann's series if the solutions are in contact with sulfides for a considerable time.

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PART II

Primary Dispersion Patterns of Heavy Metals in Carbonate and Quartz Monzonite Wall Rocks

H. T. Morris

Primary dispersion gradients of lead, copper, and zinc, slightly modified by supergene solutions locally, have been recognized in the Tintic district, Utah, in hydrothermally altered wall rocks of gold- and silver-bearing lead-zinc-copper veins in monzonite and in dolomite near lead-zinc replacement ore bodies.

The metal content of the rocks near ore decreases logarithmically, and the plotted curves strongly suggest diffusion from a short-lived source. This probably reflects rapid precipitation and a concomitant drop in concentration of the metal ions in the mineralizing solution.

Evidence was found of supergene leaching and precipitation of zinc in the wall rocks near ore bodies in the oxidized zone above the water table, but lead is apparently static under surface conditions and reflects primary dispersion patterns. Copper appears to be static in a carbonate environment but moves locally in hydrothermally altered monzonite.

The dispersion patterns of lead in the oxidized zone—and locally too of zinc and copper—compare favorably with those adjacent to primary sulfide ore bodies 700 feet below the water table, 3000 feet below the surface, where evidence of supergene movement of zinc is totally lacking.

SYNTHETIC SODIUM-, AMMONIUM-, AND HYDROGENURANOSPINITE

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Compounds isostructural with meta-torbernite-I and having the formula $A_2(UO_2)_2(AsO_4)_2 \cdot 8H_2O$, where A = Na or NH_4, have been synthesized by base exchange with hydrogen-uranospinite, $H_2(UO_2)_2(AsO_4)_2 \cdot 8H_2O$. Hydrogen-uranospinite is ditetragonal-dipyramidal; crystals are flat tablets on {001} with {010} and {1'0}. X-ray study by the Weissenberg method gave the space group P4/nmm and cell dimensions a_0 7.16 Å, c_0 8.80 ($a_0:c_0$ = 1:1.230). Specific gravity 3.55 (meas.), 3.55 (calc.). Color lemon-yellow. Perfect cleavage {001}. Optically uniaxial negative (−) with nO 1.612 (pale lemon-yellow), nE 1.584 (nearly colorless). Sodium-uranospinite has cell dimensions a_0 = 7.12 Å, c_0 = 8.70 ($a_0:c_0$ = 1:1.222), obtained by powder method. Specific gravity 3.71 (calc.). Optically uniaxial negative (−) with nO 1.617 (pale yellow), nE 1.586 (colorless). Ammonium-uranospinite has cell dimensions a_0 7.21 Å, c_0 8.85 ($a_0:c_0$ = 1:1.227), by powder method. Specific gravity 3.60 (calc.). Optically uniaxial negative (−) with nO 1.611 (pale yellow), nE 1.601 (colorless). All fluoresce bright lemon-yellow in long-wave ultraviolet radiation and less brightly in short-wave ultraviolet radiation. The relation of these substances to natural troegerite and uranospinite is discussed.

HYDRATION AND BASE-EXCHANGE PROPERTIES OF CARNOTITE, TYUYAMUNITE, AND RELATED COMPOUNDS*

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Hydrated uranyl vanadates of potassium, ammonium, thallium, calcium, strontium, barium, sodium, copper, and zinc were synthesized as part of a mineralogic study of carnotite and tyuyamunite. Microscopic and electron-microscopic examination show the crystals to be diamond-shaped plates with micaceous cleavage.

On the basis of x-ray powder patterns, these compounds may be classified into two structural types:

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Type I. Compounds of K, NH_4, and Tl.
Type II. Compounds of Ca, Sr, Ba, Na, Cu, and Zn.

The two types of compounds also differ greatly in the degree of hydration. Type I compounds contain about 1 molecule of water in the air-dried state; type II compounds, 5 to 9 molecules. The higher hydration of type II compounds may be correlated with the presence of low-angle, basal reflections in their x-ray powder patterns.

The water molecules and the characteristic cations (K, NH_4, Ca, etc.) occur between uranyl vanadate layers, a condition analogous to that found in the clay mineral montmorillonite. There is a progressive decrease in the interlayer spacing of type II compounds as water is removed by heating.

Type II compounds, when treated with solution of potassium salts, rapidly exchange their cations for potassium and are converted to carnotite. This entails a contraction of the interlayer spacing as the lower hydration characterisitc of type I is assumed. The reverse process, the conversion of carnotite to compounds of type II, involves the expansion of interlayer spacing and takes place much less readily.

SECOND SOUTH AMERICAN OCCURRENCE OF BRAZILIANITE

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In the pegmatite of the *alto* Patrimonio, at Piedras Lavradas, Paraíba, Brazil, massive amblygonite is cut by veins and patches of brazilianite accompanied by wardite, apatite, and other phosphates. The brazilianite occurs in small (1–2-mm.) grains and crystals, some fairly well developed. Measurable crystals show the following forms: (110), (010), (320) (130) (670)?, ($\bar{1}$01) (301), (021)? ($\bar{1}$11), (321), (121). The mineral was identified by indices, crystal form, and X-ray pattern. The associated wardite is somewhat coarser-grained, shows a good cleavage, and is sometimes in crude crystals. In the veins, wardite is earliest, followed by brazilianite (usually idiomorphic) and purplish apatite. In the patches, a very finely fibrous greenish mineral, resembling hydroxy-apatite; wardite, brazilianite, and apatite follow in that order, with some overlapping, and all are covered by a very fine-grained compact white mineral which may be metavariscite.

MESOZOIC AND CENOZOIC SEDIMENTARY VOLUMES IN CENTRAL GULF COAST

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Gulfward-dipping Mesozoic and Cenozoic sediments underlie approximately 145,000 square miles in the Central Gulf Coast between Texas on the west and Georgia on the east. Pre-Cretaceous, Lower Cretaceous, and early Upper Cretaceous rocks are predominantly red-bed clastics in the eastern portion of this area; westward and downdip marine facies predominate. Extensive marine deposits constitute the middle and late Upper Cretaceous; arenaceous facies predominate in the east, while argillaceous and calcareous facies are prevalent westward and downdip. Tertiary deltaic sediments center in Louisiana and Mississippi; eastward and downdip marine deposits prevail. Fluviatile and deltaic Quaternary deposits occur as a surficial mantle over much of the Central Gulf Coast; offshore these deposits are replaced by marine facies.

Stratigraphic studies indicate that major Jurassic and Lower Cretaceous sedimentary units are typically elongate-lenticular, while those of the Upper Cretaceous and Cenozoic are ladle-shaped. During Jurassic and Cretaceous times the major source of sediments was apparently eastern United States. In the Cenozoic appreciable quantities of material appear to have come from western United States.

Regional isopachous maps illustrate variations in thickness of Mesozoic and Cenozoic stratigraphic units. In the emerged (onshore) portion of the plain deep wells prove the presence of at least 257,000 cubic miles of sediments. Interpolations based on regional studies indicate that the total volume of Mesozoic and Cenozoic deposits in this area will exceed 300,000 cubic miles.

The known volumes of sediments that accumulated in the emerged (onshore) portion of the Central Gulf Coast during these times are:

	Cubic miles
CENOZOIC	102,400
Quaternary	1,000
Tertiary	101,400
Mio-Pliocene (?)	4,700
Miocene	26,300
Upper Eocene-Oligocene	5,600
Middle Eocene	16,925
Paleocene-Lower Eocene	47,875
MESOZOIC	154,875
Cretaceous	99,375
Gulfian	40,175
Coahuilan-Comanchean	59,175
Upper Jurassic	29,025
Pre-Upper Jurassic (?)	26,500

Few data are available on volumes of sediments in the submerged (offshore) portion of the plain. Conservatively, it is estimated that at least 200,000 cubic miles of Mesozoic and Cenozoic deposits are present. On the other hand, some evidence indicates the total may exceed 500,000 cubic miles.

STRUCTURE AND STRATIGRAPHY OF THE BLUE RIDGE MOUNTAIN AREA OF ALBEMARLE AND ADJACENT COUNTIES, VIRGINIA

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The Blue Ridge Mountains in this area are an overturned anticline with the axial plane dipping approximately 30° SE. and a thrust fault bordering the mountains on the western edge. There is an angular unconformity between the Unicoi formation and the Erwin quartzite, which is considered the base of the Cambrian. There is no great unconformity between the Unicoi formation and the Catoctin greenstone. Flows of greenstone occur in the base of the Unicoi formation. Where the granodiorite occurs it is separated from the overlying Catoctin greenstone by about 400 feet of metamorphosed sediments and igneous material resting on the eroded surface of the granodiorite. To the east around Charlottesville, where the granodiorite is absent, metamorphosed sediments, many thousands of feet thick, occur between the base of the Catoctin greenstone and the top of the Lovingston quartz monzonite which is the Precambrian basement complex. Above the eroded surface of this basement complex occurs the 800-foot Rockfish conglomerate and above it the Lynchburg gneiss which is separated from the Catoctin greenstone by formations described and named in this report.

INFLUENCE OF PERMEABILITY ON ORE DISTRIBUTION IN LIMESTONE AND DOLOMITE

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The general knowledge of rock permeability has been reviewed in the light of fundamental work done since Rove's pioneer study, and an attempt has been made to evaluate the influence of permeability on ore distribution in limestone and dolomite. Over 1000 permeability determinations were made, principally on rocks from the East Tennessee Zinc District. A permeameter is described

which was especially designed to measure permeabilities in the range 10^{-3} to 10^{-7} millidarcies, using either liquid or gas as the test fluid.

The potential sources of error in using gas-flow results to predict liquid flow through rocks are discussed with particular note being given to Klinkenberg's discovery that only at infinite mean gas pressure will "gas permeability" approximate "liquid permeability".

In the East Tennessee Zinc District the permeability values fall into three main groups corresponding to the three principal rock types: "original" dolomites, limestone, and "recrystalline", the latter an alteration product of the limestone near mineralization. Alteration of certain beds by the mineralizing solutions prior to sulphide introduction increased their permeability many fold; disseminated replacement ore is virtually restricted to these beds. Calculations from test results show that, under reasonable geologic conditions, large volumes of aqueous solutions can pass through rocks of the "recrystalline" type. In all probability a sufficient volume of dilute ore solution could pass through these rocks to account for all the ore deposits found in them.

CHAZYAN STRATIGRAPHY WEST OF THE CHAMPLAIN THRUST, NEW YORK AND VERMONT

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Lower middle Ordovician Day Point (oldest), Crown Point, and Valcour limestones of the type Chazy are in part redefined in terms of complete, easily accessible sections. Definition of members and zones aids in correlation. Present and previous classifications are compared.

Day Point basal quartz sands and succeeding cross-laminated, locally reefy calcarenites are shallower-water deposits of a transgressing sea. Southward-overlapping Crown Point limestones are preponderantly deeper-water argillicalcisiltites, but locally, and particularly toward the top, are *Stromatocerium* reefs. Lower limestones of the offlapping Valcour tend to match the facies of underlying Crown Point. Calcarenites characterize the upper Valcour.

Upper Crown Point reefs are most widespread, forming a roughly linear, discontinuous trend from near Isle La Motte, Vt., south to Essex, N. Y.

Most effective reef builders were *Stromatocerium* spp. Trilobites and nautiloids were most abundant reef dwellers; brachiopods and gastropods relatively uncommon. Few Chazyan species were confined to reefs. *Glaphurus pustulatus* (Walcott) (basal Valcourian) is an important exception.

Fracture of heavier shells and sorting of coarse, encrinal flank deposits indicate turbulence over reefs. Low initial dips on flanks show slight relief of reef structures.

Rapid reef to basinal facies changes are accompanied by divergence at rates up to 75 feet a mile. Reef-facies thickness in Crown Point sections bears an inverse relationship to formational thickness.

Reefs are interpreted as small bank reefs from which finer sediments were winnowed; distribution is linked with that of tectonically less negative areas.

X-RAY EXAMINATION OF URANOTHORITE

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Earlier x-ray studies of thorite have indicated that it is metamict (Vegard, Phil. Mag., vol. 32, p. 65, 1916) or have led to cell dimensions (Boldyrev *et al.*, Leningrad, Inst. Mines, Ann., vol. 11, p. 1, 1938) that seem very much out of line with those of related materials.

Single-crystal x-ray diffraction patterns have been obtained from unaltered uranothorite from Gillespie's Beach, South Westland, New Zealand. Rotation patterns on the a and c axes are very similar to zircon patterns but show a certain amount of streaking of the spots along "powder arcs". A cell of dimensions a_0 7.12Å, c_0 6.32Å contains 4ThSiO. Th is substituted by U in the ratio of about

1/7. Observed and calculated densities agree at 6.7 ± 0.05. The space group is $D_{4h}^{19} - 14/amd$. The similarity of the rotation patterns to those of zircon leaves no doubt that the structure of this uranothorite is of the H3 (zircon) type.

ORIGIN OF THE UPLAND SILT IN THE FAIRBANKS AREA, ALASKA*

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Well-sorted tan silt is widespread on the uplands below elevations of 1800 feet in much of central Alaska, especially near major rivers. Near Fairbanks, on the north side of the wide Tanana River Valley adjacent to the Yukon-Tanana Upland, the silt is 1 to 80 feet thick on tops of low hills 50 to 150 feet above the valley floor. It is 10 to 100 feet thick on middle slopes of higher hills, thinning out on the higher slopes of ridges 800 to 2000 feet above the valley. Much silt has been transported to creek valleys by streams and mass wasting, thus forming deposits of valley fill 10 to 300 feet thick. During this transportation some silt incorporated great amounts of organic material.

Suggested origins of the silt deposits are residual, lacustrine, fluviatile, and eolian. Although some of the silt may be residual, especially in areas underlain by schist, field evidence indicates that the bulk of it is eolian and was derived from glacial outwash.

Evidence for an eolian origin of the silt in the Fairbanks area is: (1) the silt occurs as a surficial mantle; (2) it is lithologically independent of the underlying material; (3) stratification is indistinct or absent; (4) it is associated with sand dunes and ventifacts; (5) it contains fossils of air-breathing land animals; (6) the sorting and texture are similar to Mississippi Valley loess and wind-blown dust; (7) the grains are angular and relatively fresh; and (8) loess is being deposited in the region today.

SOURCE AND MOVEMENT OF THE HEART MOUNTAIN THRUST BLOCKS, PARK COUNTY, WYOMING*

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Recent field work on the Heart Mountain thrust sheet in Park County, Wyoming, has extended known limits of the thrust fault about 17 miles.

Remnants of the thrust block occur in an area 50 miles long and 10 to 20 miles wide. The remnants have a maximum diameter of more than 4 miles. The thrust sheet contains only the Madison limestone (Mississippian) and older formations, which have a combined thickness of about 1700 feet. The thrust block remnants rest on formations ranging in age from Upper Cambrian to Eocene. Where the Bighorn dolomite (Ordovician) in the thrust sheet rests on the Gallatin formation (Upper Cambrian), little stratigraphic displacement is involved, but the strata in the thrust sheet are broken and displaced by numerous faults. Vertebrate fossils date the thrust faulting as lower to middle Eocene. A conglomerate derived from Madison and older formations observed at three localities indicates that these formations were exposed to erosion prior to extrusion of the volcanics of the Absaroka Mountains.

After anticlinal uplift of the Beartooth Mountains, strata at the top of the uplift above the resistant Madison limestone were removed by erosion and conglomerate was deposited. Strata down to the base of the Bighorn dolomite were then sheared from the underlying Gallatin and were moved, probably with the aid of gravity, southeastward down the south limb of the Beartooth Mountain uplift.

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Previous stratigraphic work on formations within the thrust blocks has not generally recognized the extensive faulting which may involve these formations.

MAGNETITE DEPOSITS OF THE CLINTON COUNTY DISTRICT, NEW YORK*

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The Clinton County magnetite deposits are in the Precambrian complex of the Adirondacks in the extreme northeast corner of New York State. The Republic Steel Corporation operates two mines in the area: the Chateaugay, an underground mine, in the village of Lyon Mountain, and the 81 mine near the village of Standish. The 81 mine is an open cut, but plans have been made to follow the ore bodies underground when necessary.

The foliated Precambrian rocks in the district include the following units in order of decreasing age: metasediments of the Grenville series, anorthosite, the Hawkeye granite gneiss, quartz syenite gneiss, and the Lyon Mountain granite gneiss. Numerous bodies of amphibolite occur throughout the area. The amphibolites are of different relative ages within the Precambrian and include both metamorphosed sedimentary and metamorphosed igneous rocks. The Precambrian complex is intricately folded. Both small and large faults may be observed. The Precambrian rocks show mineral lineation. The common type of lineation is parallel to the regional fold axes. A less common type of lineation occurs down the dip of the foliation and at right angles to the fold axes.

The magnetite concentrations replace a variety of rock types within the areas underlain by the Lyon Mountain granite gneiss. The most important magnetite zones are in pyroxene-rich microperthite granite gneiss, plagioclase granite gneiss, and pyroxene-rich plagioclase granite gneiss. Some of the mineralized zones have black hematite (martite) associated with the magnetite. In some areas, as at Arnold Hill, hematite is more abundant than magnetite. Sulfide minerals are rare throughout the district. Gangue minerals, besides the dominant minerals of the host rocks, include apatite, sphene, and, more rarely, fluorite. Many of the magnetite bodies occur as cigarlike shoots along the limbs and keels of synclines. The plunge of the shoots is parallel to the plunge of the mineral lineation and fold axes of the surrounding rocks. The magnetite probably owes its origin to the penetration of vapors along microshear structures in the Lyon Mountain granite gneiss. The vapors are assumed to have included iron chlorides or fluorides from which, by later hydrolysis, magnetite was deposited.

ANION EXCHANGE IN CLAY MINERALS

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The amount and nature of the anion exchange in various clay minerals were determined using electrodialyzed materials. The effect of the chloride, sulphate, and phosphate ions was determined and compared with the base-exchange capacity of these clay minerals. A tentative explanation regarding the ion-exchange phenomena was developed as a result of this study. It is suggested that in kaolinite and illite the ion exchange, both anionic and cationic, takes place on "active spots" primarily due to broken valence bonds. In the case of montmorillonite, where cation exchange may result also from excess negative lattice charge, a similar exchange may take place with anions due to excess positive charge. As a consequence of this, clays probably are not amphoteric in the usual chemical sense.

As further evidence, additional data were obtained on the effect of particle size on the cation- and anion-exchange capacity of these clay minerals. The anion-exchange capacity in kaolinite was shown

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to depend on the lateral surface area of the clay mineral. The relationship existing between anion-exchange capacity and lateral surface area was also demonstrated for other clay minerals.

HARRISBURG (SILVER REEF) MINING DISTRICT, WASHINGTON COUNTY, UTAH

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The Silver Reef mining area in southwestern Utah contains the only known occurrence in the United States of commercial bodies of silver ore with minor copper-uranium-vanadium minerals in sandstone. The ore bodies are restricted to the Silver Reef sandstone member of the Upper Triassic Chinle formation and occur on the limbs and nose of a major anticline and a subsidiary anticline and syncline. A newly recognized north-trending normal fault and a thrust fault with a minimum eastward displacement of 1500 feet repeat the ore horizon three times. No observable relationship exists between the mineralization and the folds or faults.

Silver, copper, and minor gold values in a bentonite 300 feet below the ore-bearing horizon, minerals of these metals and lenselike bentonitic shales in the Silver Reef sandstone, and other known occurrences of notable metal content in volcanic tuffs suggest a new theory of origin for these unusual deposits. The metals were primary constituents of original volcanic tuffs in Triassic time. These metals were dissolved and/or mechanically transported by streams eroding the tuffaceous sediments and were later deposited with the sandstone and shales of the Silver Reef area. Further concentration of the metals in the Silver Reef sandstone was by (1) solution in circulating ground waters, and (2) precipitation because of contact with entombed plant debris and associated bacteria in more permeable buried Triassic stream channels. Folding, erosion, and exposure of the ore horizon resulted in secondary enrichment of the ore deposits by meteoric waters.

GEOMORPHOLOGY AS A TOOL FOR GEOLOGISTS

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Many pioneer workers in geomorphology were concerned primarily with developing a terminology for the science and in the classification of "pure" landforms. Although the importance of *structure*, *process*, and *stage* was early acknowledged, the emphasis was chiefly on *stage*.

Geomorphology in the future should be increasingly concerned with the recognition of *process* and evaluation of its effectiveness on rocks of unlike resistance exposed in various environments. Great advances have been made in allied fields, and these must be used if the science is to advance. To cite a case: the aerial photograph is among the more powerful tools now available and may prove to have as revolutionary effect on landform interpretation as the topographic map did in the nineteenth century.

This paper reviews the present status of geomorphology and discusses some of the ways in which it may be used as an aid in stratigraphic, tectonic, and engineering geology. An example is the use of warped terraces in estimating the amount and nature of Recent deformation.

BONAPARTE GULF BASIN OF NORTHWEST AUSTRALIA*

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The Bonaparte Gulf basin comprises an area of Paleozoic rocks bordering the Bonaparte Gulf of northwest Australia. This sedimentary basin is about 200 miles long and 30–50 miles wide and is

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occupied by 6000–8000 feet of Devonian, Carboniferous, and Permian marine and fresh-water sediments, which unconformably overlie Middle and Lower Cambrian rocks. The Middle Cambrian consists chiefly of fresh-water sediments with marine intercalations containing a new species of trilobite of the genus *Solenoparia*, previously known only from the Middle and Upper Cambrian of Asia. Basalts, underlying the Middle Cambrian strata, are presumed to be Lower Cambrian. They overlie several thousand feet of quartzitic sandstones and shales thought to be Upper Precambrian. The latter in turn overlie, with a marked unconformity, closely folded metamorphic and igneous rocks presumably of Archean age.

The Cambrian and Upper Precambrian rocks are sharply folded and faulted. The Upper Paleozoic formations show little deformation except that due to fault dislocations and the compaction of sediments over and around Devonian limestone reefs.

The main features of the geology of the Bonaparte Gulf basin were determined by the author in 1947 during aerial and ground reconnaissance surveys of the region made for Standard-Vacuum Oil Company and Associates. The presence of Paleozoic rocks along the northwest coast, however, had been known earlier from discoveries by Australian geologists of Upper Paleozoic fossils at several isolated localities in the region, but until the author's investigation in 1947 the boundaries of the basin had not been determined, and very little was known about its geology.

PALEOGEOGRAPHIC AND STRATIGRAPHIC SIGNIFICANCE OF SUBAQUEOUS FLOW MARKINGS IN THE LOWER MISSISSIPPIAN STRATA OF SOUTH-CENTRAL OHIO AND ADJACENT PARTS OF KENTUCKY

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Flow markings appearing as casts on the under sides of Lower Mississippian siltstone beds are found over a large area in south-central Ohio and adjacent north-central Kentucky; all show strong lineation in directions varying little more than 10° from east-west. Wherever definite determination can be made, the flow was from the east.

These markings are interpreted as having been made on the underlying shales by density currents of silt-laden water flowing down a foreset slope (clinoform) being built westward into deeper water during the time of deposition.

If this interpretation is correct, the paleogeographic and stratigraphic implications are far-reaching, for beds so deposited would not be correlative with each other in the direction of the flow markings, though they might be so in the strike direction of the foreset slope (clinoform) at right angles to the markings. Correlation of beds so deposited on the hypothesis of their having been deposited horizontally, one above the other, would be erroneous. Age and lithology would not coincide, and isopach maps of lithologic units would have little paleogeographic significance, as sketches to be presented will show.

GEOLOGY ALONG THE WILLIAMS THRUST NEAR KREMMLING, COLORADO

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Kremmling is in the western part of the depression known as Middle Park in north-central Colorado. Precambrian rocks in the area are overlain by 100 feet of the Jurassic Morrison formation and 6000 feet of Upper Cretaceous rocks including the Dakota sandstone, Benton shale, Niobrara limestone, and Pierre shale. Above the Pierre with no evident angular discordance at the contact is the Middle Park formation of late Cretaceous and Paleocene age. An extensive volcanic breccia of probably Eocene age in the northern part of the area unconformably overlies all the older forma-

tions. This breccia and all older rocks are in turn overlain by clays and sands of lower Oligocene(?) to upper Miocene or Pliocene age.

The horizontal to east-dipping Williams thrust enters the Kremmling area from the south where the trace is along the west side of the Williams River Range. It was mapped for 20 miles north of this range to Gunsight Pass where it disappears under volcanics. Throughout much of the intervening area the trace is concealed by volcanic breccia or younger sediments. Remnants exposed are mostly klippen of Precambrian rock resting on Mesozoic sediments. The principal movement on the thrust was after the deposition of the Middle Park formation but before the extrusion of the Eocene volcanics. In late Eocene time local renewed movement followed the formation of the volcanic breccia.

ANALYSIS OF THE METHODS OF STORING INVERTEBRATE FOSSILS

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There is no perfect method of storing fossils. A method that is very satisfactory for one individual or museum will be found impractical for another. An attempt has been made to survey some of the important museums and universities in North America, and abroad, to determine the methods used to store their invertebrate fossils. Consideration was given to the scope and special needs of the various collections. The two main methods are systematic and stratigraphic, with numerous subheadings of each. A preliminary analysis of the answers received to date shows a strong preference for a stratigraphic method, especially on the part of those museums devoted primarily to research. When an institution is engaged in teaching, it is frequently found desirable to maintain two collections, one filed stratigraphically and the other systematically, the emphasis depending upon whether the teaching stresses systematic or stratigraphic paleontology. A series of tables will be presented to show the results of the survey.

INTERSTADIAL SOILS AS POSSIBLE STRATIGRAPHIC HORIZONS IN WISCONSIN CHRONOLOGY*

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Wisconsin glacial deposits in various parts of the Rocky Mountains, the Great Basin, the High Plains, the Mississippi Basin, and New England are intercalated with soils that originated during interstadial intervals. Within each region two to five soils of different ages can be distinguished by differences in profile development (primarily thickness and color of the oxidized horizon) and can be stratigraphically related to the local succession of glacial or related deposits. Coincidence in relative degree of development with stratigraphic position of the soils in the different regions suggests that the soils may be correlated with one another.

The first and third Wisconsin interstadials are characterized by buried humus zones, peat accumulations, or partly leached zones, though these soils have not yet been observed in all the regions. The second interstadial is characterized by soils having relatively thick and strongly colored oxidized zones. The fourth interstadial is characterized by soils distinctly less oxidized than soils of the second interstadial. A fifth interstadial is characterized by soils that are still less well developed. Very weakly developed soils or no soil have formed on deposits of the latest glacial advance.

Though soils of any given interstadial differ from one region to another, the relative differences between soils of different interstadials remain surprisingly constant. The constancy of these differences and the demonstrable relationship of the soils to Wisconsin stratigraphy suggest that soils are *bona fide* stratigraphic horizons, reliable both within and beyond the limits of glaciation.

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STRENGTH OF LIMESTONE

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A new investigation of the strength of fine-grained limestone has been made under confining pressures up to 4000 atmospheres. Special consideration was given in the experiments to the following: jacketing the specimens from contact with the liquid pressure medium, application of stress to the limestone specimens in several different ways, the effect of time on the manner of failure, and the effect of specimen size. The two modes of failure observed were by rupture and by flow, and the strengths found with each stress system seem to be consistent for both types of failure. A tentative theoretical analysis of the criteria for failure indicates adequate regularity for prediction of failure. The behavior under experimental conditions seems to be analogous to the rupture and flow of limestone under geologic conditions.

PROBLEM OF POROSITY

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Replicate bulk densities and grain densities were measured on 42 randomly selected samples from two outcrops of the Oswego graywacke in Central Pennsylvania and on 37 randomly selected samples of the Third Bradford sand from the Bradford Oil Field, Pennsylvania. In addition, effective porosities to three different fluids on 111 Bradford subsamples were measured.

Specific questions were asked concerning each of the three sampled areas, and all experiments were statistically designed to answer these questions. Examples of questions asked are: (1) Do different beds in the Oswego have different porosity? (2) Do different levels in a single outcrop have different porosity? (3) Does the Bradford sand have the same effective porosity to water, kerosene, and tetrachloroethane? (4) What is the inch-to-inch subsample variation in porosity for these sands?

The contributory effects of beds, levels, subsamples, operators, replication, fluid differences, and residual error to the total variation in porosity were analyzed by use of several patterns of analysis of variance. The combination of experimental design and statistical treatment of results yielded "probability stated" answers to all of the questions, despite relatively large experimental error.

A survey of over 300 publications reveals that, despite a multiplicity of different methods (at least 300, if minor modifications are included), the solution to the problem of porosity measurement remains elusive. The fundamental problem does not appear to be one of experimental technique but rather one of experimental design and statistical control so that clearly formulated questions can be unequivocally answered.

ONTOGENETIC DEVELOPMENT OF SELECTED LOWER ORDOVICIAN TRILOBITES

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Silicified trilobites from the Garden City formation of northeastern Utah reveal the existence of three kinds of protaspids, which can be classed as "normal" opisthoparian, proparian, and a strongly convex, subovoid, enrolled opisthoparian type. The last two of these bear three pairs of spines; only in the proparians does any pair appear to develop into genal spines of the adult. Facial sutures are developed in the smallest specimens of all three kinds.

Ontogeny of two proparian species throws doubt on the theory of initial diagonal segmentation and suggests the existence of a "preantennal" segment in the protaspids discrete from the frontal glabellar lobe.

Pygidial development of a species of *Macropyge* (opisthoparian) indicates that the metaprotaspid period continues until the pygidium is composed of a telsonlike spine plus eight firmly welded segments. During the meraspid period segments are shed successively into the thorax to form the eight thoracic segments of the adult, leaving only the telson as the holaspid pygidium. The full number of body segments is attained before meraspid development begins.

Some of the subovoid protaspids have been linked to an *Apatokephalus*-like species. These are trilobed, but appear to lack transverse segmentation. The anterior of the three pairs of spines is strongest; it is maintained until the axial length of the meraspid cranidium exceeds 0.6 mm., but is lost before the length reaches 0.95 mm. Genal spines are developed separately from either of the other pairs.

NEW WORK ON BED OF LAKE DAKOTA, SOUTH DAKOTA

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This lake bed had been known for many years and was mapped for a U.S.G.S. Folio fifty years ago. The new work consists in mapping many marginal features, several deltas, and studying the sediments, mostly clays, beyond the deltas. Many drillings into and through the sediments have been made, and several outcrops have been studied. The lake was 98 miles north and south and 4-25 miles wide, and was held in on the south by a very bouldery moraine.

While thus retained, the silts accumulated over feeble ground-moraine surface to the thickness of 10 to 16 feet. Some deltas are several miles in extent. Sand from the James River delta in the lake has been blown into many dunes along the eastern margin.

FURNACE ATMOSPHERE CONTROL IN DIFFERENTIAL THERMAL ANALYSIS

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The usefulness of differential thermal analysis can be extended considerably by controlling the composition of the furnace atmosphere. The method described for securing atmosphere control is applicable to most existing differential thermal-analysis furnaces. Examples are given which show the effect of a furnace atmosphere of nitrogen on differential thermal curves of clays containing organic matter and pyrite. Other curves show the effect of CO_2 on differential thermal curves of siderite, magnesite, dolomite, and calcite. One curve follows the alternate dissociation—reconstitution of the $CaCO_3$ part of dolomite in an atmosphere of CO_2. The effect on the differential thermal-analysis curve, of filling the furnace with a gas which is a participant in the reaction, is explained by the relation of the partial pressure to the equilibrium constant and the heat of reaction. (Publication No. 10, Exploration & Production Research Division, Shell Oil Company, Houston, Texas.)

GEOLOGIC HISTORY OF SEA-WATER*

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If the history of the oceans and atmosphere were known, and also that of changes in their composition, it would throw light on other problems that confront geologists; but a review of the literature reveals little agreement about this history. It has been suggested that the early seas carried more dissolved Fe and Mg and the later seas more Na and K, that the early atmosphere was rich

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in CO_2, and that sea-water has become continuously more saline. Yet the mineral and fossil content of sedimentary rocks indicate that the composition of sea-water and atmosphere has varied only slightly since early geologic time. A primary problem is how conditions could have remained so nearly constant for so long.

It is clear, even from inadequate data on the quantities and composition of continental and deep-sea sediments, that the more volatile materials—H_2O, C, Cl, N, and S—are much too abundant in the atmosphere, hydrosphere, and ancient sediments to be explained, like the other materials, as the products of rock weathering. If the earth were once entirely gaseous or molten, these "excess" volatiles probably condensed from a primitive atmosphere; but advancing knowledge in seismology and geochemistry makes it increasingly difficult to retain the concept of an originally molten earth. The relative amounts of these "excess" volatiles correspond fairly well with those in gases from volcanoes and hot springs and in igneous rocks. Conceivably the hydrosphere and atmosphere may have come almost entirely from the earth's interior.

Hot springs are concentrated in areas of relatively young mountains and intrusive rocks; and they may be partly the result of hot gases forced out from crystallizing magmas. If hot springs carry a per cent or so of such juvenile materials, their present rate of flow is sufficient to account for all the hydrosphere and atmosphere.

This would imply that the volume of the ocean has grown with time. On this point, geologic evidence permits differences of interpretation; but the record seems consistent with an increasing contrast between continental masses and oceanic basins and with a progressive sinking of the basins. Perhaps something like the following mechanism could account for a continuous escape of volatiles to the earth's surface and a relatively uniform composition of sea-water through much of geologic time:

1) selective fusion of lower melting fractions from deep-seated, nearly anhydrous rocks beneath the unstable continental margins and geosynclines;

2) rise of these selected fractions (as granitic and hydrous magmas) and their slow crystallization nearer the surface;

3) essentially continuous isostatic readjustment between the differentiating continental masses and adjacent ocean basins; and

4) renewed erosion and sedimentation, with resulting instability of continental margins and mountainous areas and a new round of selective fusion below.

RECLASSIFICATION AND CORRELATION OF THE GLACIAL DRIFTS OF NORTHWESTERN IOWA AND ADJACENT AREAS*

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Topographic, lithologic, and stratigraphic evidences show that four Wisconsin drifts occur in northwestern Iowa and southwestern Minnesota. Two drifts (Iowan and Mankato) were recognized previously. The Iowan passes under a younger drift, the Tazewell, along a line from Carroll County, Iowa, to the head of the Coteau des Prairies in eastern South Dakota. The Tazewell drift is bordered on the east by the Bemis marginal moraine of the Des Moines lobe. The Altamont moraine of the lobe overrides the Bemis in eastern South Dakota and in northwestern Iowa. The Des Moines lobe therefore is believed to consist of two drifts, Cary (drift of the Bemis moraine) and Mankato (drift of the Altamont and younger moraines).

Four Wisconsin loesses, each related to its respective drift, are recognized. Continuous, well-sorted loesses that thin from west to east and that were derived from a distant major source cover the Iowan and Tazewell drifts. Thin, variable-textured loesses derived from local sources cover the Cary and Mankato drifts discontinuously.

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Iowan and Tazewell drift surfaces are well drained, whereas Cary and Mankato surfaces are undrained. Contrast of stages of surface drainage indicates that the Tazewell-Cary interstadial was longer than the Iowan-Tazewell and the Cary-Mankato intervals.

A buried soil in the Wisconsin loess in western Iowa probably represents weathering during the Tazewell-Cary interstadial. The Brady soil of Nebraska and Kansas may be correlative of the Tazewell-Cary interstadial soil of Iowa.

ORIGIN OF A LAYERED ULTRAMYLONITE FROM SOUTHEASTERN CONNECTICUT

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At the southernmost contact of the Preston gabbro is a zone of imbricate structure in which the hydrothermally altered gabbro and four tabular bodies of chlorite-actinolite schist derived from it have been brought into juxtaposition with a block of medium-rank gneiss and its progressively mylonitized equivalents. The lower 5 feet of the exposed part of the block of nonlayered biotite-cummingtonite-hornblende gneiss was converted to a layered slatelike ultramylonite composed of alternating quartz-plagioclase laminae and biotite-amphibole laminae which range in thickness from a thin film to 5 mm. The ultramylonite has a well-developed cleavage parallel to the lamination. The temperatures that prevailed during mylonitization were apparently high enough to prevent significant diaphthoresis and low enough to prevent recrystallization. The block is at least 20 feet thick, and it exhibits all stages of cataclastic reduction and increasing metamorphic differentiation from top to bottom. No transposition of s-planes was involved, and the dip of the foliation in all the cataclastic rocks is parallel to the uniformly dipping reverse faults. The ultramylonite was subjected to post-layering microfaulting.

The origin of the layering is discussed in the light of the solution principle of Eskola, the mechanical hypothesis of Schmidt and Wenk, and the complex hypothesis of Sander and Turner. It is concluded that the process of metamorphic differentiation was dominantly mechanical and a consequence of the difference in mechanical behavior of the light and dark minerals under shearing stress. The degree of perfection of the lamination is believed to be a function of the kinematics of the mass during mylonitization.

GEOLOGIC SECTION AND SUCCESSION OF HUMAN CULTURES IN THE LATE PLEISTOCENE OF THE CLOVIS-PORTALES REGION, EASTERN NEW MEXICO

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The locality is a small filled lake or marshy stream head from which collections were made in the 1930's by Howard, Cotter, Stock, and others, and in 1949 and 1950 by the writer and others of the Texas Memorial Museum. The lake-filled section consists of four members or horizons, each separated from the other by a disconformity. The basal member, a gray sand, contains chiefly Columbian elephant, horse, and bison. The artifacts at this level include projectile point of the Clovis fluted type, hammer stone, bone points, and implements of split bone. The second member consisting of dark sand, in which no artifacts have been found, contains abundant bison. The third member, which is diatomaceous, contains a great abundance of bison, *B. taylori*, but no elephant or horse. The artifacts of the third horizon are of the Folsom culture. The fourth member, consisting of clay and dark sand, contains abundant fossil bison species not determined and "Yuma" type artifacts.

The split-bone culture with Clovis fluted projectile points is older at this locality than the Folsom culture, and the Folsom culture in turn is older than the "Yuma" cultures, which include the Eden, Scotts Bluff, and other projectile points. The elephant and horse existed at this locality contempo-

raneously with bison, but disappeared when the bison became excessively abundant. The interruptions in deposition, causing disconformities and in places erosion, in the lake deposits probably indicate changes of climate from wet to dry; at least four such fluctuations are indicated.

NEEDS OF MODERN RESEARCH IN PHYSICAL GEOMORPHOLOGY

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These remarks pertain to physical geomorphology and only incidentally to the equally important historical aspects of the science. The greatest current need is for closer association with physics and geophysics. The following propositions are advanced:

(1) Deductive geomorphology as practiced by Davis and other masters has been a productive and stimulating procedure. It should not be abandoned, but the need at present is for a critical examination, checking, and testing of deductive concepts already advanced rather than additional stockpiling of unfounded deductions. Preliminary data derived from a study of Cima Dome, a classical desert dome, are offered in support of this proposition.

(2) Physical geomorphology must be firmly based in all disciplines of geology. In addition to being a good geologist, the practicing geomorphologist will be more effective if well versed in soil science and acquainted with principles of hydraulics, meteorology, oceanography, and botany.

(3) Application of physics and geophysics to geomorphological research offers the greatest promise for fundamental advance. Examples are cited to show the value of this procedure. The needs are two: (1) for arousing the interest of physicists and geophysicists in geomorphological problems, and (2) for applying the results obtained in these fields to geomorphology. Few if any practicing geomorphologists have proper background for bridging the gap between physics and geomorphology, but recognition of the need can result in proper training of personnel for this task. Chemistry is currently revolutionizing certain aspects of biology; physics appears able to do the same for physical geomorphology.

MISSISSIPPIAN-PENNSYLVANIAN UNCONFORMITY IN SOUTHERN ILLINOIS*

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A systematic study of the Mississippian-Pennsylvanian unconformity surface in the southern portion of the Illinois basin, using both surface and subsurface data, indicates that many factors were involved in the origin and history of the erosional surface. Criteria for the subsurface recognition of the unconformity are presented, and the rocks above and below the contact are compared and contrasted. An areal geologic map of the pre-Pennsylvanian formations shows three major features: beveling of younger formations at the edges of the Illinois basin, beveling of smaller structures in the basin, and long, deep, narrow channels incised into the erosional surface. Several isopach maps indicate the configuration of the channel systems and the upland surface between channels.

The geologic history of the unconformity started with uplift and withdrawal of the sea in late Chester time and the start of a long period of subaerial erosion. A peneplain was formed which beveled structures and exposed older Chester and Lower Mississippian formations at the structurally higher basin borders. After peneplanation the area was uplifted, and a new cycle of erosion began, resulting in the incision of deep channels in the peneplain surface. In early Pennsylvanian time the front of a large piedmont alluvial fan advanced westward from the Appalachian geosyncline and buried the topography developed on the pre-Pennsylvanian formations. During and after Pennsylvanian time the unconformity was warped, folded, and faulted to give its present attitude.

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MAGNETITE DEPOSITS OF THE DOVER DISTRICT, NEW JERSEY*

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The Dover district is in the New Jersey Highlands, a region underlain by rocks of Precambrian age. About 500,000 tons of iron ore is produced annually from three mines in the district—the Scrub Oaks, Richard, and Mt. Hope.

The rocks are deformed into isoclinal folds that plunge gently to moderately northeast. Lineation is nearly parallel to the fold axes. Transverse and longitudinal faults with minor displacements offset the rocks and the ore bodies.

The magnetite deposits are high-temperature metasomatic replacements of (1) oligoclase-quartz-biotite gneiss, (2) albite-oligoclase granite, and (3) skarn. Magnetite is the principal ore mineral, although hematite constitutes 18 per cent of the ore in one deposit. Sulfides are almost absent. The deposits are on the limbs and noses of major folds. The ore bodies in gneiss and granite were localized by microbreccia zones produced by pre-ore cataclastic deformation. The deposits are lath- or ruler-shaped bodies whose longitudinal axes parallel the lineation of the country rock. Several ore bodies have been mined along their elongation for more than 1½ miles, and the end of a deposit has never been reached. The ore-forming solutions were derived from the alaskitic facies of the granite magma that consolidated to form hornblende granite, alaskite, and related facies. Continuous enrichment of this portion of the magma in iron culminated in the deposition of iron oxides. Iron-poor pegmatitic facies were split off from the granite magma and consolidated prior to the introduction of magnetite.

CRYOPEDOLOGIC PHENOMENA IN THE BEARTOOTH MOUNTAINS, WYOMING-MONTANA

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The following types of frost-induced phenomena occur on low to moderate slopes of the Beartooth upland: stone nets, stone stripes, boulder-banked terraces, block fields, block stream, amorphous rubble, and earth hummocks. The formation of these features is believed to date back in part to the time when glaciers occupied adjoining valleys.

LARGE INTRUSIVE BODIES IN THE CENTRAL COAST RANGE OF OREGON*

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Sills and sill-like bodies are the most common type of intrusive rocks in the central Coast Range of Oregon. Individual sills now cover as much as 50 square miles and are as much as 1000 feet thick. Erosional remnants of once-extensive sills form the most prominent peaks and concordant upland surfaces throughout this region. Mount Hebo, Mount Gauldy, Saddleback Mountain, Fanno Ridge, Marys Peak, Prairie Peak, and Table Mountain have maintained their altitudes because of protective igneous caps.

A late Oligocene age is suggested for the principal Coast Range sills. Evidence for such an age assignment is found at Spencer Butte where a sill that is related to the same stage of igneous activity penetrates the Eugene formation of middle Oligocene age. Subsequent to its intrusion the sill was laid bare by erosion and later was surrounded by middle Miocene basalt flows.

The large sill that forms Mount Hebo shows evidence of rapid cooling and low intrusion temperature; whereas the sill at Marys Peak shows crystal settling and thus indicates a higher intrusion temperature.

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The principal rock types found in the larger sills are granophyric gabbro, granophyric diorite, gabbro, and diorite. Camptonite and nepheline syenite are found in places along the western margin of the larger sills, and intrusives of quartz diorite are found along the eastern margin. The alkalic rocks appear to be desilicated differentiates of the original parent magma which may have approximated a gabbro magma.

COMPARISON OF ETCHED SILICIFIED OSTRACODES FROM LIMESTONE WITH CALCAREOUS FORMS FROM SUBJACENT SHALE*

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Ostracode faunas contained in limestones differ from those contained in shales of approximately the same age. Faunas in two samples of the Helms formation of Mississippian age collected at Stop 1 of the West Texas 1946 field trip: one from limestone (bed 9 of section "C," U. S. Geol. Survey Prelim. Oil and Gas Map 36) and one from a shale 6 feet stratigraphically below that limestone are compared.

The combined fauna consists of 21 species: 5 common to both samples, 9 restricted to the limestone, and 7 to the shale. Residues of two limestone beds of the Helms formation at the same locality have yielded 22 species indicating that our limestone sample does not contain a complete faunule. The shale also probably contains more species than were obtained from our sample, but it is significant that the species on hand restricted to the shale are not found in the thousands of specimens in the limestone residues.

The following hypothesis is suggested by this preliminary study: Some of the species common to both samples may be pelagic, but most probably the species of this group are benthonic and able to adapt themselves to variable environments. Species of this group should consequently be useful for local and regional correlation.

Because only two small samples were used in this study, it is premature to infer conclusions, but it is hoped that, by focusing attention on studies of this type, data from which to draw valid conclusions will eventually become available.

EXPLORATION FOR COPPER IN WALLAROO MINING DISTRICT, SOUTH AUSTRALIA

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The Wallaroo Mining District, South Australia, is on a practically flat soil-covered terrain and is devoid of outcrops. The maximum observed thickness of the soil mantle is about 20 feet. The soil section is as follows, from the Precambrian bedrock up:

(1) ***Residual reddish-brown clays***, containing little or no lime. The A-B-C type of soil profile is recognizable, as a rule. The type of weathering is ancient and is indicative of a warm pluvial climate. Thickness: 3 to 16 feet.

(2) ***Caliche limestone.*** A concretelike rock containing round limy concretions embedded in a hard limy matrix. Thickness: 2 to 8 feet.

(3) ***Modern soil***, resembling *terra rossa*, derived partly from the limestone and partly from windblown materials. Thickness less than 1 to 2 feet. This soil contains practically all of the feeder roots of the vegetation.

Approximately 2000 copper tests representing more than 8 miles of traverses show that the expression of the known chalcopyrite bodies is in the ancient residual clays and not in the limestone or in the modern soil.

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Three copper anomalies were discovered, in the reconnaissance, by testing the ancient clays for the hydrochloric acid-soluble forms of copper. The copper background in such clays was nearly zero. The anomalies were explored with diamond drills to depths exceeding 400 feet. Bands of disseminated chalcopyrite mineralization were discovered at 100 feet to 300 feet below the rock surface. The width of the bands was 1 to 20 feet, with a maximum Cu content of about 1 per cent and a prevailing Cu content of less than 0.5 per cent.

The mineralization is subeconomic, but its discovery is significant, as any kind of Cu mineralization outside the known lodes is extremely rare in the district.

There is little evidence of diffusion of copper through the rock in the vicinity of the mineralization. The copper anomalies in the ancient soils are probably due to the subeconomic analogues of the economic lodes in the parent rock. There is only a vague correspondence accordingly between the size of the copper anomalies in the soils and the intensity of the prospecting targets they represent.

CENTRIPETAL GENESIS OF MAGMATIC ORE DEPOSITS

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Laboratory data and plant experiments with blast-furnace slag have demonstrated the solubility of water in molten silicates, even under atmospheric pressure. An intruding magma, if unsaturated with respect to water, will therefore establish a gradient of both water pressure and water concentration in surrounding rocks; the direction of falling pressure and concentration will be toward the intrusive, not away from it as has been commonly assumed. This gradient is further enhanced by the phenomenon of thermal transpiration, by which a gas under constant pressure, in a medium having small pores, travels toward the region of highest temperature. The ground water in intruded sedimentary beds therefore travels toward an unsaturated intrusive [illegible]ive rock, rising in temperature as it approaches the intrusive, finally depositing its dissolved substances when it begins to vaporize preliminary to becoming incorporated in the magma. Among the dissolved substances will be compounds of copper and zinc, already concentrated from sea water by marine organisms in the sediments.

RELATION OF TYPE OF COUNTRY ROCK TO THE SHAPE OF GRANITIC PEGMATITE INTRUSIONS*

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Examination of more than 1800 pegmatite intrusions in the Quartz Creek district, Gunnison County, Colorado, has shown that the shape of a granitic pegmatite intrusion is controlled by: (1) the type and competency of country rock; (2) the composition of the pegmatite magma; and (3) the amount of intruded material. Of these, (1) is commonly the most important.

Intrusions of pegmatite in competent rocks, such as granite, monzonite, quartzite, and hornblende gneiss, commonly cut across the older layered structures such as bedding, banding, or foliation, and follow joints or other fractures, forming thin, tabular to sinuous, branching, and irregular bodies.

The pegmatites in incompetent rocks, such as mica schist, are in general concordant with foliation and were intruded by shouldering apart the country rock along foliation planes. Pegmatites of this type are commonly lenticular, troughlike, arcuate, or tear-drop-shaped; branching and irregular shapes are rare.

The pegmatites in the competent rocks tend to be thinner than those in the incompetent rocks; thickly lenticular pegmatites are practically unknown.

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All bodies of pegmatite with the same composition do not have the same shape, although in some districts lithium-bearing pegmatites tend to be bulbous. With the intrusion of large amounts of pegmatitic material, the effect of the country rock on the shape of the pegmatite is usually obscured, and the body assumes an irregular stock like shape. The type of country rock thus appears to have the greatest control over the final shape of the smaller pegmatite bodies.

Similar relations between the shape of pegmatites and the type of country rock have been found in other districts.

LOWER EOCENE BALL CLAY IN EAST TEXAS

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Ball clay is being produced near Henry's Chapel, 5 miles southeast of Troup, in Cherokee County, eastern Texas. The clay is the topmost bed of the lower Eocene Wilcox group and is separated from the overlying shaly silts of the Carrizo formation by an erosional disconformity. It can be demonstrated that the clay forms the top of a buried hill composed of Wilcox strata and is surrounded and overlain by the Carrizo formation of the Claiborne group. The buried hill is at least 77 feet high.

AGE AND STRUCTURAL CONTROL OF THE FLUORSPAR DEPOSITS IN THE NORTHGATE DISTRICT, COLORADO*

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Fluorspar of two ages occurs in the Northgate district, Colorado:

(1) Small, lenticular veins of siliceous fluorspar follow reverse faults that formed during the Laramide orogeny. The veins show successive stages of brecciation and mineral deposition and apparently formed while the faults were still active. All known veins of this type are on branch or tear faults that cut the Precambrian rocks above the main reverse faults.

(2) The larger, commercial fluorspar deposits are along normal and strike-slip faults that cut the Oligocene White River formation as well as the Precambrian crystalline rocks. These deposits are beveled by an erosion surface that was cut after the Pliocene (?) North Park formation was deposited. Structural features in the White River and North Park formations suggest two periods of minor deformation during middle and late Tertiary. The fluorspar-bearing faults probably were formed during one of these periods.

Most of the veins were deposited in open fissures or fault breccia and are typically layered or crustified. The fluorspar contains few impurities and is either finely granular or columnar and botryoidal. Cavities are numerous and range from small vugs to "water courses" several feet wide and more than 50 feet long.

The younger fluorspar was deposited largely in the relatively open fissures and breccia where the faults cut hard, brittle rocks. Precambrian Sherman granite was the most favored host rock and forms at least one wall of nearly every ore shoot now exposed.

FOLDED LOW-ANGLE OVERTHRUSTS OF THE SOUTHERN APPALACHIANS

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Folding, the first orogenic phase of the Appalachian revolution, was followed from Maryland southwestward by an overlapping series of low-angle overthrusts which formed in the rising Blue Ridge welt. In these thrusts early Precambrian basement rocks and the folded envelope of late Precambrian and Paleozoic strata of the miogeosyncline rode westward onto folded rocks of the valley.

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Erosion of these thrust plates along upwarps brought to view underlying thrust sheets in windows and semi-windows. The Grandfather Mountain window, North Carolina, a very large one recently mapped by the writers, exposes the Holston Mountain block framed by the Fries block which has undergone large-scale warping. These flat folded overthrusts rode onto the folded Pulaski block which similarly is supported by an upwarp of basement rocks. If bedding thrusts occur in the Appalachian Valley, as postulated by some, they are confined to the western part of the allochthon and were formed by the push of the easterly crystalline wedges.

East of the Blue Ridge anticlinorium, windows in the Martic overthrust expose Paleozoic sediments of an eastern carbonate sequence, marked by a Middle Cambrian unconformity and deposited in a subparallel trough east of the main miogeosyncline. Crystalline schists of the Martic block are a series of shales and effusives laid down in the eugeosyncline and thrust westward in Taconic orogeny. Appalachian thrusting, accompanied by folding, carried westward the overridden and overthrust blocks. The straight steeper thrusts, including the Brevard, Towaliga, and Canton, of the last orogenic phase preceded intrusion of epitectonic batholiths and metallogenic epochs.

OCCURRENCE OF NORTH AMERICAN SPECIES OF THE EUROPEAN AND AUSTRALIAN TETRACORAL GENUS *TRYPLASMA*

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The Silurian tetracoral genus *Tryplasma* is a member of a cognate group in which the septa are of one order and are composed of vertical rows of spines. Several North American species formerly assigned to *Cyathophyllum* and *Amplexus* are found to be species of *Tryplasma*. Species of this genus are present in the Manistique dolomite of Michigan, the Hopkinton dolomite of Iowa, the Louisville limestone of Indiana and Kentucky, the Brownsport formation of Tennessee, the Keyser limestone of Maryland and Virginia, and the Stonewall limestone of Manitoba.

GAS CONTENT AND AGE OF TEKTITES

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The gas content of the bubbles present in so-called gas-rich philippinites has been investigated, and the total gas pressure inside these bubbles was found to be exceedingly low. Although bubbles of 0.1 to 0.2 cc. volume were opened by cracking tektites in a vacuum, it was not possible to collect any measureable amount of gas. This places an upper limit of the pressure inside the bubbles of 1/1000 atmosphere.

By heating coarsely crushed tektites up to 1200°C. approximately 0.1 cc. of gas at S. T. P. per gram of tektite was released. Analysis of these gases showed, in agreement with investigations by Brun in 1909, that its main constituents were CO_2, CO, H_2O, and H_2. No argon could be detected in this gas. The upper limit for argon may be taken as 10^{-6} cc. per gram. This evidence, and the fact that philippinites contain 1–2 per cent of potassium, leads to the conclusion that the age of tektites, as determined by their gas content, must be quite small and definitely cannot be that of the solar system.

PRIMARY SEDIMENTARY STRUCTURES OF THE AUX VASES SANDSTONE*

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Type sections of the Aux Vases sandstone (basal formation of the Upper Mississippian Chester series) in eastern Missouri and the equivalent Brewerville sandstone in southwestern Illinois are in

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massive to cross-bedded sandstone bodies 30 to 100 feet thick, probably several miles long, and a few tenths to at most a few miles wide. Marginal to the best-exposed massive body is thick-bedded sandstone with rill-marked bedding surfaces and primary dips of 10° to 12° away from the massive body. Several hundred feet from the massive lens are alternating beds of nonsandy shale and pure sandstone a few inches thick. Upper surfaces of most sandstone beds have current ripples, and lower surfaces of many beds are covered with roll-like or cerebroid structures, convex downward, the shale cusps being upright in some instances but inclined or overturned in others. Amplitude of the structures ranges from about ¼ inch to several inches, is quite constant on some beds for outcrop lengths of 40 feet, and is roughly correlative with thickness of the sandstone bed. Height appears controlled to some extent by thickness of the underlying shale. The structures give a criterion for stratigraphic sequence. A tentative explanation of their origin by creep of unconsolidated sand over soft mud is advanced.

PETROGRAPHY OF THE PEORIA LOESS IN KANSAS

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Peoria loess of early Wisconsinan age is the most widespread outcropping deposit in Kansas. This loess was sampled over an area extending 400 miles east to west and 200 miles north to south. Samples were analyzed for particle size, chemical composition, and mineral constituents. In addition to examinations by petrographic microscope, X-ray diffraction patterns and electron micrographs were utilized. Particle-size data show size-frequency distributions similar to those of loess samples from elsewhere in interior North America. Within the silt fraction, major constituents are: quartz (more than half the volume of the sediment), feldspars, volcanic ash shards, carbonates, and micas. A large suite of accessory minerals was determined. The clay fraction consists of montmorillonite, illite, calcite, quartz, feldspar, and traces of a kaolinite mineral. Chemical analyses show a high degree of uniformity throughout the area of Peoria loess, and its average composition is similar to that of typical granite. Evidences of localization of source areas are: (1) progressive linear changes in texture; (2) geographic variations in thickness; and (3) minor geographic differences in composition. These data indicate that the Platte River Valley was an effective source of loess distributed widely in north-central and southwestern Kansas; that the Arikaree, Arkansas, and Republican rivers were important supplementary sources; and that the Missouri River was a predominant source of loess in northeastern Kansas. Such principal valleys as Big Blue, Solomon, Saline, and Smoky Hill (which carried no late Pleistocene outwash) were not sources of Peoria loess.

FAUNA AND PALEOECOLOGY OF THE UPPER CAMBRIAN WARRIOR FORMATION OF CENTRAL PENNSYLVANIA

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This paper presents the results of a systematic study of the Smithsonian Warrior collection augmented by the Pennsylvania State College and the writer's own collections in the upper part of the formation.

The Warrior trilobite fauna is expanded by 1 new genus, 24 new species, and 3 new varieties. Burrowing kingstonid trilobites were most abundant. Next most frequent, in descending order, were species of *Coosella*, *Blountia*, *Genevievella*, and *Lonchocephalus*. Sparsely represented were species of *Pemphigaspis* and *Tricrepicephalus*. Rare trilobites included species of *Bonneterrina*, *Norwoodina*, *Welleraspis*, and *Ithycephalus*.

At the type locality, Warriorsmark, a *Cedaria* fauna appears to overlie a *Crepicephalus* fauna. In the Warrior outcrops east of Waddle, a *Crepicephalus* fauna is underlain by a *Cedaria* fauna. Here

the two zones are clearly demarcated. At the same locality, the *Cedaria* fauna may be underlain by a *Crepicephalus* fauna. The "key" genera, *Ankoura*, *Genevievella*, *Norwoodina*, *Bonneterrina* of the *Cedaria* zone are found in the same horizon with the "key" genera of the *Crepicephalus* zone, an occurrence differing from that reported in the middle west. Previous assignment of *Crepicephalus* zone age for the upper three-fourths of the Warrior is not supported by the present evidence.

Cyclical occurrence of Cryptozoon reefs and the appearance of fossiliferous oölitic limestones and edgewise conglomerates in inter-reef periods during late Warrior time are interpreted as indicating a cycle of alternations from warm, clear, shallow-water conditions to turbid-water and tidal-flat conditions.

PIEDMONT INTERSTREAM SURFACES OF THE COLORADO SPRINGS REGION

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Two major groups of piedmont surfaces, designated the High and Low Level groups of late Pleistocene age, flank the Front Range in the Colorado Springs region. A restricted group, intermediate in elevation, is also present. Recent terraces occur in the broad valleys below the piedmont levels.

The piedmont surfaces slope outward from the range and truncate the homoclinal structure of the mountainward edge of the Colorado Piedmont. They consist of roughly planate bedrock levels, thinly blanketed with poorly sorted and poorly stratified fanglomerate.

The development of these features is related to processes now active in the valley bottoms. A multiple arrangement exists with minor vertical intervals separating the several member levels of each group, and major vertical intervals separating the groups. Each level is the uplifted remnant of a former valley bottom developed during an episode of valley widening. Vertical intervals between the levels represent episodes of valley deepening.

The Front Range is being continuously uplifted. Valley widening is accomplished by sidewall retreat controlled by uniformly semiarid climate which yields constancy in the rates of erosion and weathering. Vertical scour by shifting torrents is responsible for corrasion of the bedrock surfaces to approximate flatness. Valley deepening is related to climatic fluctuation toward more humid conditions, yielding continuous runoff along a confined locus of flow. The continuous uplift then promotes deep incision of the drainage line. Alternation of the climatic regime in this fashion is responsible for the multiplicity in occurrence of the surfaces. The variations in climate may be related to the incidence of glacial and interglacial conditions in the Southern Rocky Mountains during the Pleistocene.

GEOLOGY OF THE WALLAPAI DISTRICT, ARIZONA

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The Wallapai district is in the Cerbat Mountains, a range composed of crystalline rocks, most of which are presumably Precambrian in age. The oldest rocks are quartzite, mica schist, hornblende-diopside schist, and amphibolite. Younger and larger in amount are granite and granite gneiss. Gabbroic and dioritic gneiss, pegmatite, aplite, diabase, and mylonite also occur as part of the basement complex. The earliest rocks were strongly folded, but igneous intrusion and granitization have obliterated most of the folds. The rock types and the history of the basement complex compare closely with the Archean in the Grand Canyon.

The district contains no Paleozoic rocks and probably no Mesozoic rocks. Intrusions of granite porphyry associated with mineralization are believed to be Tertiary in age. Dikes of granite porphyry, pegmatite, aplite, and lamprophyre are associated with these intrusions.

Small areas of andesitic and rhyolitic extrusive rocks, of Tertiary (?) age, occur along the flanks of the range. Quaternary basalt caps these rocks in some places.

Several periods of faulting and erosion are visible in the volcanic rocks. The latest faulting has produced the present mountains. The greatest displacement has been on the west side, and the Cerbat Range is an eastward-tilted fault block, modified in part into a horst. This mountan building seems to have occurred in late Tertiary and Quaternary time. Recent fault-block movement is suggested by the presence of canyon terraces and by the dissection of the pediment at the west base of the range.

ARTESIAN HORIZON BENEATH McNARY DAM, OREGON

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McNary Dam, a multi-purpose structure being built under direction of the U. S. Corps of Engineers, is located on the Columbia River 292 miles above its mouth.

Foundation rock is the Columbia River basalt, a thick series of Miocene flows with local sedimentary interbeds, which has been gently folded and faulted.

Subsurface investigations, commencing in 1923 and continued up to the present, have established the extent and physical characteristics of an artesian horizon underlying the site. During early studies, its presence was the cause of apprehension because of the possibility of leakage and dangerous uplift pressures that might be associated with raising the pool if the aquifer outcropped close by within the reservoir. Testing, consisting of conventional and large-size borings, determination of rates of percolation, comparisons of thermal and chemical properties of the artesian and river water, pump tests to determine piping tendencies within the aquifer, and the long-time recording of piezometric pressures within the suspect horizon led to the conclusion that there was no close-by upstream point of infiltration and that an extensive grout curtain to attempt to block the artesian aquifer as proposed initially was not justified. It is planned to continue measurements of pressure within the aquifer after the reservoir is in operation. If these indicate the desirability of grouting, it can be done later fully as effectively as at the present.

LATE CENOZOIC HISTORY OF THE WABASH AREA, INDIANA*

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A bedrock topographic map of the Wabash area, Indiana, reveals a buried peneplain that is about 700 feet in altitude and is correlative with the Lexington peneplain of southern Indiana and Kentucky. The preglacial Kanawha Valley (Teays) crosses the area and contains two major physiographic features: (1) a prominent terrace about 100 feet below the peneplain, correlated with the Parker strath; (2) the gorgelike "deep stage" of the valley which is cut some 200 feet below the terrace. The peneplain and terrace were developed late in the Tertiary, and the "deep stage" probably early in the Pleistocene.

Only Tazewell and Cary glacial materials are exposed. The broad, flat Mississinewa moraine marks the outer limits of the Cary till. Extensive outwash was deposited in the Eel, Mississinewa, and Wabash sluiceways. Two prominent terraces occur along the Wabash sluiceway. The upper, Mississinewa, terrace is 40 to 50 feet above the flood plain and represents the upper limits of valley filling. The lower, Maumee, terrace is 20 to 25 feet below the Mississinewa terrace and is a remnant of the surface eroded by the overflow waters of Lake Maumee.

The Wabash Valley is superposed upon glacial drift and bedrock which constitute alternating stretches of its walls. The Wabash Valley widens markedly where it crosses the buried Teays. Late-glacial and postglacial streams have exhumed Silurian bioherms and thus produced the many klintar which are so prominent along all the sluiceways except the Eel.

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VOLUME OF CENOZOIC SEDIMENTS IN GEORGIA AND FLORIDA

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Cenozoic sediments having a maximum thickness of 3000 feet and an average thickness of 1500 feet underlie an area of 33,000 square miles in southern Georgia. The thickness increases at a rather regular rate from the northern edge of the outcrop southeastward. The total volume of Cenozoic sediments in Georgia is more than 9000 cubic miles.

Cenozoic deposits underlie all of Florida, an area of 58,560 square miles. During the Cenozoic there were two main basins of deposition. One, centered west of northwestern Florida and extending into the western edge of the State, contains predominantly clastic deposits. The other, in the southern part of the peninsula, contains only carbonate rocks. Cenozoic sediments are thinnest near the north-central part of the peninsula in the outcrop area of the Ocala limestone. The total volume of Cenozoic sediments in Florida is more than 40,000 cubic miles.

Thicknesses of the Cenozoic divisions are shown by isopachous maps and cross sections. Comparative volumes of sediments are illustrated by diagrams.

FROST ACTION ON EXCAVATED SLOPES IN NIOBRARA CHALK, FORT RANDALL DAM, SOUTH DAKOTA

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Corps of Engineers, Pickstown, S. D.

The combined effects of moisture and temperature variations associated with frost action seriously altered the wall of Cretaceous Niobrara chalk designed as 4 on 1 slopes around the excavation for the outlet works at Fort Randall Dam, on Missouri River in South Dakota.

In view of equally steep natural slopes which are stable in Niobrara chalk in the vicinity, it was anticipated that uniform 4 on 1 slopes, formed by vertical coal-saw cuts with set-back benches at 30- to 50-foot intervals, would be stable during the construction period. The chalk slopes thus formed during the spring and summer remained stable throughout the winter; however, spalling began the following spring when seasonal temperature raised sufficiently to promote thawing. Seasoning of the slopes, during the summer months, was not sufficient to provide a protective layer against direct exposure of pore moisture to freezing. Although the ultimate design required placement of concrete on some slopes and backfilling adjacent concrete walls on others, the uncontrolled spalling in the spring produced safety hazards during construction. Treatment of sections potentially hazardous to structural design was accomplished by pinning the spalling material to firm chalk with grouted anchor bars.

Future design, on permanent open-cut excavations, will feature 1 on 1 slopes as a measure of reducing the hazards developed by loose pieces of chalk. Temporary exposures of chalk, requiring concrete placement and backfilling, will follow the 4 on 1 pattern, however; specification will require that final concrete and backfill construction be accomplished prior to late fall and winter seasons.

OBSERVATIONS ON TWIN LAWS COMMONLY EXHIBITED BY PLAGIOCLASE OF METAMORPHIC ROCKS

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Observations on the twin laws commonly exhibited by metamorphic (especially by deformed) rocks are placed on record. Attention is drawn to the marked contrast between the complex association of twins typical of plagioclase in igneous rocks, and the much less complex twinning of metamorphic plagioclase, as a possible basis for distinguishing:

(1) metasomatic from magmatic plagioclase in granitic rocks;
(2) relict from metamorphic plagioclase in amphibolites.

FABRIC OF YULE MARBLE DEFORMED EXPERIMENTALLY AT ORDINARY TEMPERATURES IN ABSENCE OF WATER

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During the past year a series of cylinders of Yule marble have been deformed experimentally at room temperature, under 10,000 atmospheres confining pressure, dry. Cylinders were cut parallel, at 45°, and perpendicular to foliation of marble. For each orientation, both compression and extension tests were made, giving shortening or elongation of 3 to 20 per cent. Strain of 40 per cent was achieved in two cases.

For strains of 15 per cent or less the original pattern of preferred orientation of calcite grains (with c axes at high angles to foliation) is surprisingly little changed. There is a slight tendency for crystal axes a_1, a_2, and a_3 to become oriented in some cases. Lamellae parallel to $\{01\bar{1}2\}$ develop profusely as deformation proceeds. Most of these appear as sharply defined lines rather than twin bands, even where deformation is strong and lamellae closely packed. Nevertheless closely packed lamellae are always those on which the resolved shear stress is high in the direction and sense necessary for twin gliding. Recorded strain for the specimen is too great to be accounted for by twinning alone, even if it be assumed that all observed lamellae are twinned. In view of the relatively undisturbed state of the space-lattice orientation and the predominance of lamellae it is concluded that half, or more, of the deformation is due to translation gliding on $\{01\bar{1}2\}$.

Bell's discovery of translation gliding on $\{01\bar{1}2\}$ in calcite has been confirmed in single-crystal experiments.

In specimens deformed 20 per cent or more in tension there is evidence of much more complete twinning of suitably oriented grains.

GROWTH OF WATER-SOLUBLE AND OTHER CRYSTALS AT LOW TEMPERATURES

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Crystals have been synthesized at low temperatures from (1) water solutions, (2) melts with or without temperature-gradient conditions, and (3) hydrothermal processes. Extensive investigations have been made in crystal synthesis directly from aqueous solutions. Outstanding success has been attained with Rochelle Salts, ammonium dihydrogen phosphate, and ethylene diamine tartrate, by various investigators in the United States and elsewhere. Numerous other inorganic and organic crystals have been grown readily. Although few of these crystals occur in nature, the principles involved in their synthesis are of interest to the mineralogist and geologist because the mechanics of growth may be similar to those of natural water-soluble crystals. It is of more than passing interest, however, that NaCl crystals of large size are crystallized commercially from melt at high temperatures. Certain organic crystals have been synthesized by crystallization from a low-temperature melt using a temperature-gradient method similar to that employed successfully for commercial synthesis of NaCl and CaF_2 at higher temperatures. The Signal Corps Engineering Laboratories at Fort Monmouth, New Jersey, have been engaged actively in synthesis of berlinite ($AlPO_4$) since 1946. More recently this organization has synthesized $AlAsO_4$. Both of these crystalline materials are synthesized hydrothermally at or below 250°C; both are unusual in that they have retrograde solubility characteristics. Tourmaline has been synthesized on a small scale from natural source materials at low temperatures for the Signal Corps by Baird Associates, Cambridge, Massachusetts. Considerable data have been accumulated showing that quartz crystal can be synthesized at low temperatures (250°C). Although synthesis of the last two minerals at low temperatures has no practical value at this time, geologic implications are evident.

HUMMERITE AND MONTROSEITE, TWO NEW VANADIUM MINERALS FROM MONTROSE COUNTY, COLORADO*

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Two new minerals, collected in the summer of 1949, are described and compared with previously known vanadium minerals from Colorado.

Hummerite was first identified in bright-orange veins in gray clay at the Hummer mine of the Jo Dandy Group on the southwest side of Paradox Valley, Montrose County, Colorado, and later as a yellow efflorescence on sandstone at the North Star mine on the opposite side of Paradox Valley. It is translucent, water soluble, and similar in appearance to pascoite but has the composition hydrous potassium magnesium vanadate. The X-ray powder pattern of crystals formed by evaporation of a water solution is the same as that of the original vein mineral. The recrystallized material is triclinic, pinacoidal class, and forms crystals elongated parallel to the c axis or tabular parallel to the b and c axes. It is optically negative, has strong dispersion, and $n_Y = 1.81$. The chemical analysis and morphologic and X-ray crystal data will be presented.

Montroseite, in black microscopic bladed crystals, was found in the Bitter Creek mine on the northeast side of Paradox Valley, Montrose County, Colorado. It is orthorhombic, probably rhombic-dipyramidal class, opaque, and has the composition $2FeO \cdot V_2O_3 \cdot 7V_2O_4 \cdot 4H_2O$. Morphologic and X-ray crystal data are presented together with spectrographic and chemical analyses.

SURFACE STRUCTURE AND CRYSTAL GROWTH

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The concept that the cube face of a crystal having NaCl structure consists of a checkered pattern emanating positive and negative force fields represents an idealization which is useless for explaining the surface properties of a large number of crystals. It is not understandable on this basis why sintering of calcined MgO should require the very high temperature it does and why it can be accomplished at a much lower temperature if certain "impurities" are present. An explanation for this and related phenomena is presented on the basis that crystals containing ions of widely different polarizabilities develop surfaces which contain primarily the most polarizable ion in the extreme outer layer, followed by the less polarizable ion which is slightly recessed. This deviation of the surface from the bulk structure can lead to an electrical double layer setting up repulsion forces between the single particles and thus preventing sintering.

The surface structure depends largely on the surrounding medium, a fact which can be demonstrated by the change in the hydrophilic and the catalytical properties of PbF_2 and HgI_2 on removal of the water layer.

These concepts are applied to the crystallization of substances from various solvents as affected by impurities.

LATE TERTIARY THRUSTING IN NORTHEASTERN NEVADA†

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Low-angle thrust faulting involving late Tertiary lacustrine sediments occurs in two areas in eastern Elko County, Nevada.

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Along U. S. Highway 93 in the valley west of Spruce Mountain Mississippian (?) limestones similar to those exposed at the base of Spruce Mountain override siltstones and sandstones of the Humboldt formation. Although the net slip is unknown, it exceeds 3½ miles. The same fault is exposed about 10 miles southward (T.29N., R.63E.) immediately northeast of the Cherry Creek Range. Here an isolated mountain of Middle Permian and Lower Triassic rocks occurs as a klippe resting on similar lacustrine sediments. The thrust zone is nearly horizontal, and the overridden rocks are only moderately deformed.

The second area lies about 62 miles north of Spruce Mountain in Thousand Springs Valley (T.41 and 42 N., R.66E.), east of Knoll Mountain. This fault appears to dip gently westward, with minimum displacement of about 5 miles. The lake beds beneath the thrust are highly deformed. The Permian limestones above the fault have relatively gentle dips.

The thrusting in both areas was preceded and followed by normal faulting.

The presence of lower Pliocene (?) camelids in the lake beds at both localities, together with the lithologic similarity of the sediments to those of known early Pliocene age, indicates that thrusting occurred in post-early Pliocene time.

Similar thrust faults, but not necessarily involving the Humboldt formation, occur at several other localities in northeastern Nevada, and the indication is strong that low-angle thrusting played an important part in the tectonic history of the region.

POTASSIUM CONTENT OF MARINE SEDIMENTS

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Investigation of the radioactivity of sedimentary rocks in oil fields, sponsored by The Geological Society of America and the American Petroleum Institute, has included 450 measurements in duplicate of the potassium content of eight geological formations. Samples of the East Texas Cretaceous are from Trask's collection of oil-well cuttings; others are of cores furnished by oil companies.

The sediments studied include sandy shales and sandstones (Tuscaloosa and Woodbine), normal shales (Eagle Ford and Eutaw), shales high in organic material (Cherokee and California phosphatic Nodular), and chalks. The samples are dissolved in hydrofluoric and sulfuric acids and evaporated to dryness. The residue is redissolved in dilute hydrochloric acid, and this solution is filtered to remove alkaline earth sulphates and organic carbon. The potassium content of aliquot parts of the filtrate is determined, with a precision of 2 per cent, by means of a Perkin-Elmer flame-photometer.

The average potassium value for each formation is computed statistically by frequency-distribution methods. The variability of the formation in potassium is taken as the quantity equal to twice the standard deviation. About 95 per cent of the measurements fall within this range above and below the average.

TWO SILICIFIED MIDDLE ORDOVICIAN TRILOBITES

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Forty species of trilobites have been obtained from limestones of the Edinburg formation in the Shenandoah Valley, Virginia, by dissolving in hydrochloric acid. The silicified exoskeletons are dissociated, but most of the parts of the majority of the species have been recognized, and in many cases developmental stages occur. One species of *Ceratocephala* is completely known, and a reconstruction has been prepared. This extremely spinose genus is widespread in Silurian and Devonian rocks, and the spinosity suggests a floating or swimming habit. In the smallest cranidia the glabella is parallel-sided, without lateral lobes, and possesses six pairs of axial spines. With increasing size the posterior part of the glabella becomes relatively larger, and the lobation is developed.

Holia has been known previously only from the Kimmswick Limestone of Missouri and Illinois. Sufficient material to reconstruct the exoskeleton has been found, and the cheirurid affinities of the genus are confirmed. The thoracic pleurae have the transverse row of pits. The pygidium is short and bears one pair of long, upcurved pleural spines. The smallest cranidia known have two pairs of spines on the lateral borders, situated in front of the long genal spines. With increasing size these spines are reduced and are represented by tubercles in the adult. The eye lobe moves inward and backward during development, and the posterior part of the glabella becomes relatively larger.

UPPER CAMBRIAN TRILOBITES FROM THE WELGE SANDSTONE, EASTERN LLANO UPLIFT, TEXAS

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In the eastern Llano Uplift, the base of the 12-foot Welge sandstone member of the Wilberns formation contains abundant fragments of the following trilobites: a new species of an undescribed genus common in the lowest Ore limestone of Pennsylvania, *Cheilocephalus* n. sp., a large *Plataspella* n. sp., *Elvinia* n. sp., *Elvinia roemeri* (Shumard), and pygidial fragments of *Pterocephalia* and *Camaraspis*.

The new species listed are not known in the later *Elvinia* fauna of the immediately overlying Morgan Creek member, nor elsewhere in the typical development of that fauna over the mid-continent area. This important faunule represents the earliest known occurrence of mid-continent lower Franconian trilobites. In Texas it forms a new subdivision, the lowest of three in the *Elvinia* faunizone:

Irvingella major faunizone

Elvinia faunizone
- (3) *Dellea suada-Burnetia urania* assemblage (20 to 50 feet above the base of the Morgan Creek member)
- (2) *Plataspella anatina-Kindbladia wichitaensis* assemblage (basal reddish Morgan Creek member and higher Welge member)
- (1) Basal Welge assemblage (lower 3 feet of the Welge member)

The faunule is confined to a 2- or 3-foot bed of coarse calcareous ferruginous white and yellow sandstone occurring only on the eastern side of the uplift between nonresistant beds of highly glauconitic sandstone. This bed is considered basal Welge, but the Welge contact with the underlying Lion Mountain greensands (Dresbachian-Franconian boundary) is not as well defined here as in the western uplift.

SUPPOSED PRIMATES FROM THE TORREJON FAUNA OF THE NACIMIENTO FORMATION

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Although primates have been long known from rocks of Torrejonian (middle Paleocene) age, these mammals have remained unrecorded from the type fauna of the San Juan Basin, New Mexico. In 1948 and again in 1950, specimens of primatelike aspect were obtained by the University of Kansas from the Nacimiento formation as exposed in the Kutz Canyon drainage a few miles west of Angels Peak. These specimens, of Torrejonian age, seemingly are to be assigned to the Order Primates. They may be regarded tentatively as anaptomorphids, and closest to members of the Paromomyinae. The upper molars exhibit basining of the posterointernal parts characteristic of this group, but differ from those of described genera insofar as known in the development of a distinct metacone on the fourth premolar. Two genera, one or both new, are represented by upper jaws. Lower jaws were also recovered, but these are less well preserved, less definitely primate in habitus. The latter seem-

ingly do not represent more than a single generic group, and cannot be assigned with certainty to either of the two groups indicated by the upper jaws.

PETROLOGY OF THE ALKALINE ROCKS OF THE NEMURO DISTRICT, HOKKAIDO, JAPAN

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In the Nemuro Peninsula, alkaline rocks occur in the Cretaceous formations as sheets, laccoliths, or rarely as submarine flows. Their age is probably upper Cretaceous or lower Tertiary. The rocks vary from picritic trachydolerite, trachydolerite, and trachybasalt to monzonitic and syenitic rocks. Minerals present, which often show zonal structures, include plagioclase, anorthoclase, orthoclase, analcite, natrolite, thomsonite, augite, aegirine-augite, olivine, biotite, and iron ores. The preponderance of K_2O over Na_2O is remarkable, and the Peacock alkali-lime index is 52.1.

The margins of thick sheets or laccoliths are chilled porphyritic trachybasalt. Dark picritic trachydolerite rich in olivine and augite lies immediately above the lower chilled margin and grades upward into less dark trachydolerite and monzonitic rocks near the upper chilled margin. The materials only within the chilled margins are occasionally cut by syenitic veins ranging in thickness from a few inches to a foot. Thus gravitational differentiation *in situ* is inferred to have occurred in these intrusive bodies.

Various parts of the pillow structure, which is sometimes well developed in the thinner sheets, show noticeable differences in texture as well as in chemical composition. It is argued that crystallization in an extremely water-rich magma rather than under a water cover is responsible for the formation of the pillows.

The original magma of these alkaline rocks was probably shonkinitic in composition, with abundant volatile components, which played an important role in crystallization, especially in the late magmatic and hydrothermal stages.

COMPLETE SUBSTITUTION OF ALUMINUM FOR SILICON: THE SYSTEM $3MnO \cdot Al_2O_3 \cdot 3SiO_2$—$3Y_2O_3 \cdot 5Al_2O_3$

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Thermal, optical, and X-ray data indicate that there is a complete series of solid solutions between spessartite, $Mn_3Al_2(SiO_4)_3$ and yttrogarnet, $Y_3Al_5(AlO_4)_3$. The substitution $Y^{+3}Al^{+3} \rightarrow Mn^{+2}Si^{+4}$ may be represented by the formula:

$$(Mn_{3-x}\ Y_x)\ Al_2\ (Si_{3-x}\ Al_x)\ O_{12}.$$

Yttrogarnet has a cube edge of 12.01 ± 0.02 A and the space group O_h^{10}. Using the co-ordinates of grossularite as determined by Menzer, good agreement was obtained between calculated and observed intensities. The atomic positions are:

Al in 16(a)	0	0	0
Y in 24(c)	$\frac{1}{8}$	$\frac{1}{8}$	0
Al in 24(d)	$\frac{3}{8}$	$\frac{1}{8}$	0
O in 96(h)	x	y	z

where x, y, and z are 0.04, 0.055, and 0.64 respectively. The yttrium is in eight-fold co-ordination; the aluminum is in both four- and six-fold co-ordination. Yttrogarnet inverts to a high form at approximately $1970° \pm 50°$ C.

This is the first case on record of the complete substitution of aluminum for silicon in an orthosilicate. It contradicts the prevalent idea that the substitution of aluminum for silicon always decreases as the Si/O ratio decreases.

MECHANISM OF VEIL FORMATION IN CRYSTALS*

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Numerous observers have reported that there is a maximum practical rate of crystal growth. Crystals grown at faster rates invariably develop flaws—veils. These veils are lines, planes, or bodies of liquid and gaseous inclusions commonly oriented with respect to some growing face. One expects that, when a seed is planted in a saturated solution, there will be considerable veiling to make the adjustment of the seed to the equilibrium endform of the crystal. Thereafter when the endform is in equilibrium with the solution, growth at a slow rate should proceed with a high degree of perfection. Experience with laboratory growth of numerous crystals together with pilot plant growth of ADP is drawn upon to elaborate a mechanism of veil formation and of crystal growth from water solution. Examples of natural crystals can be used to support the general picture.

ORIGIN OF BEDROCK LAKES IN NORTHEASTERN MINNESOTA

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The Border Lakes region of northeastern Minnesota is characterized by three main types of bedrock—the Saganaga granite (Laurentian), Duluth gabbro (Middle Keweenawan), and the Rove slates (Huronian) with associated diabase sills (Middle Keweenawan).

Bedrock lakes within each of the three areas of bedrock have a distinct relation to the structure and lithology of the rocks. Segments of Saganaga Lake in the Saganaga granite are parallel to east-west and north-south joints. Bedrock lakes in the Duluth gabbro are elongated in the direction of the east-west bands of different mineralogic composition in the gabbro. Rock-bound lakes in the Rove area lie in bands of slate which strike east-west and dip gently south. The slate bands are separated by cuestalike ridges of diabase. Lakes in the Rove area have asymmetrical bottom configurations, and some are over 200 feet deep. Lakes in the gabbro have symmetrical bottom configurations and an average depth of 20 to 25 feet.

Glacial striae indicate that the general direction of movement of the Wisconsin continental glacier was from north to south, a direction at right angles to the "grain" of the topography in most of the Border Lakes region. The origin and configuration of the bedrock lakes is explained on the basis of *selective glacial erosion* operating in conjunction with obstructed extrusion flow.

REPORT OF COMMITTEE ON RADIOACTIVE CARBON 14

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Radiocarbon assay of many specimens of wood, peat, charcoal, and organic mud from upper Pleistocene stratigraphic positions has been performed at the Institute for Nuclear Studies, The University of Chicago, in consultation with a joint committee of the American Anthropological Association and the Geological Society of America.

Although the results are subject to several possible errors, the dates obtained fall generally into the same order as the related stratigraphic sequence. The dates are generally more recent than had

* The material in this talk will be published under the authorship of P. H. Egli, S. Zerfoss, and S. Siawson.

been believed by many, although they appear consistent with the slight alteration and erosion of the latest glacial drift sheets. Thus the Two Creeks horizon in Wisconsin, immediately antedating the Mankato glacial maximum, proves to be only about 11,400 years old. Pollen-dated deposits from Europe correlate well with this horizon, suggesting contemporaneous climatic variation.

The dates of post-Mankato-maximum samples afford a consistent chronology. Some of them suggest that late phases of the glacial Great Lakes were very short lived. Expectably, samples of Sangamon and Illinoian materials were found to lie beyond the present reach of radiocarbon assay, which is about 20,000 years. Three samples from deposits of the Tazewell-Cary interval were found to be older than 15,000–17,000 years, with no maximum limit determined. Hence the date of the Cary glacial maximum is not yet fixed.

Refinement of laboratory methods is expected to extend considerably the present range of dating. The committee will continue actively to promote the determination of as many significant dates as possible.

ABSTRACTS OF PAPERS SUBMITTED TO MEETING AT SEATTLE, WASH., APRIL 7–8, 1950

CORDILLERAN SECTION OF THE GEOLOGICAL SOCIETY OF AMERICA

AGES OF PLUVIAL LAKE SHORE LINES OF SOUTH-CENTRAL OREGON

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The multiplicity of shore lines surrounding the former pluvial lakes in the fault troughs of south-central Oregon poses problems of correlation with their corresponding glacial stages. Although certain shore lines generally have been considered equivalent to the Tahoe and Tioga glacial stages of the Sierra Nevada, some of the oldest and highest ones may well record lake levels of pre-Wisconsin time, perhaps as old as Kansan or Sherwin time. Otherwise the lack of older shore lines is very puzzling.

SPILITES AND QUARTZ PORPHYRIES IN THE CANTON OF GLARUS (SWISS ALPS)

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The lowest part of the Helvetic nappes of Glarus includes a considerable number of flows and sills of spilites, quartz porphyries, and allied pyroclastics. They are associated with slates, sandstones, and conglomerates of Permo-Carboniferous age and represent probably the final phase of the magmatic activity of the Hercynian orogeny.

The spilites vary greatly in grain size, texture, and structure, and indicate the presence of a great amount of volatiles during the main period of crystallization. More than half the minerals are albites of different generations. Olivine, augite, and ilmenite, the earliest minerals to crystallize, are nearly everywhere altered. The groundmass varies from chlorite-epidote-calcite (in the earlier extrusions) to albite-hematite-quartz (in the latest extrusions). Chemical analyses and the mineralogic variation show a differentiation from an older spilitic to a younger keratophyric magma. Primary textures and absence of zoned plagioclase indicate that albite, chlorite, calcite, and epidote are primary. An accumulation of residual solutions (mainly H_2O and CO_2) caused the lowering of temperature previous to the main and late phase of crystallization, and was responsible for the spilitic mineral association. The quartz porphyries are rich in large phenocrysts in a cryptocrystalline or microcrystalline groundmass. Flow structure is present in most of these rocks. Their pyroclastics consist to a great extent of ignimbrites, and their chemical composition is very much the same as that of other alpine quartz porphyries.

MULTIPLE GLACIATION IN THE WHITE RIVER VALLEY NEAR ENUMCLAW, WASHINGTON

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Two Pleistocene glacial stages were recognized in the Puget Lowland by Willis (1898) and Bretz (1913), chiefly on the basis of stratigraphic relations in the central part of the Lowland. Mapping in the drift border areas, with weathering as a criterion, Mackin distinguishes two stages, Wisconsin and Illinoian (?), and scattered erosion remnants of deeply weathered early Pleistocene till. Excavations made in construction of the Mud Mountain dam in the White River Valley near the Cascade front provide exposures in which the early Pleistocene deposits include two separate till sheets; a thoroughly decomposed zone at the top of the lower till indicates that two early Pleistocene ages are represented. These tills are overlain, in the same cuts, by the Illinoian (?) and Wisconsin tills, with interbedded peat and fluvial and lacustrine sediments. The Mud Mountain excavation, showing

three and possibly four major glacial stages, is a key section for the Pleistocene stratigraphy of western Washington.

All the Mud Mountain tills were formed by glaciers descending the White River Valley from the Cascades. Generally speaking, the White River cut a valley into each of the successive fills during the next interglacial. The positions of the interglacial valleys and the permeability of the fills in them bear on the tightness of the Mud Mountain reservoir.

SALINES AT CARBONATE LAKE, GRANT COUNTY, WASHINGTON*

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Carbonate Lake, a potential source of sodium carbonate, is about 10 miles west of Warden, a station on the main line of the Milwaukee Railroad. It lies in an undrained, deep basin in a tract of basaltic scabland just east of Crab Creek; the bedrock bottom of the basin is below the water table and also below the level of Crab Creek.

Production of sodium carbonate was never commercially successful because of high operating costs, technical difficulties in purifying the product, and problems of marketing.

The solid salts form surface crusts, separate lenses in the lake mud up to a depth of 8½ feet, disseminated crystals in mud, and a bed at the bottom of brine pools; their composition (analyses by Benson, Moulton, and Hebner), recalculated to a mud-free basis, ranges between 64 and 87 per cent sodium carbonate, 4 to 30 per cent sodium sulphate, 1 to 7 per cent sodium chloride, and 0.7 per cent potassium sulphate. Brine, which occurs underground and in perennial pools, has a specific gravity up to 1.37 and averages roughly 52 per cent sodium carbonate, 22 per cent sodium sulphate, 21 per cent sodium chloride, and 5 per cent potassium sulphate; qualitative spectrographic analyses by Grant M. Valentine show, in addition, the presence of calcium, iron, strontium, aluminum, silicon, and magnesium.

The salts include natron, mirabilite, thenardite, halite, aphthitalite, trona, gaylussite, nahcolite, and a hydrous double salt of sodium sulphate and sodium carbonate.

UPPER CRETACEOUS-EOCENE(?) NANAIMO GROUP OF THE SAN JUAN ISLANDS, WASHINGTON

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Nanaimo strata occur in a northwest-trending belt on the northernmost San Juan Islands. The sediments are predominantly conglomerate and graywacke. The graywackes are normally cross-bedded and generally contain conglomeratic layers. Conglomerates up to boulder size contain fragments of all earlier rock units in the area, including some friable shale.

Faunal assemblages of the four known localities indicate brackish(?) to marine environments of late Cretaceous age. Conglomerates of the Chuckanut formation, assigned to the Eocene on plant evidence, are indistinguishable from the "Cretaceous" conglomerates immediately above the Cretaceous faunal horizons. Thus the Nanaimo group may be in part post-Cretaceous.

Regionally, these sediments indicate rapid and near-source sedimentation and are regarded as transitional between the predominantly marine deposition to the northwest and the predominantly continental deposition to the southeast. The Nanaimo sediments appear to have accumulated in a northwest-trending structural trough extending from northwestern Washington through the Straits of Georgia.

KYANITE PARAGENESIS AT OGILBY, CALIFORNIA

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The major commercial production of kyanite in the Western States has been from an occurrence of the west flank of the Cargo Muchacho Mountains, near Ogilby, California. Here a series of predominantly pelitic sediments (the Vitrefrax formation of Henshaw) has been regionally metamor-

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phosed and invaded by tonalite, adamellite, and granite. The rocks of the Vitrefrax formation are chiefly muscovite and quartz-muscovite schists, with subordinate quartzite. The principal concentrations of kyanite, in which the arrangement of the crystals approaches a decussate texture, are confined to the more quartzose portions of the Vitrefrax formation. Here, in addition to the dominant kyanite and quartz, muscovite and magnetite commonly occur in varying minor amounts. Many divergences from this characteristic assemblage occur. A kyanite-quartz-muscovite-biotite-staurolite-garnet assemblage is known. Tourmaline is locally concentrated, as is apatite. Dumortierite (rare) appears to form at the expense of kyanite. Evidence for at least local hydrothermal concentration of kyanite is afforded by association of unusually large crystals with vein quartz and by growth of kyanite crystals along fractures athwart the regional schistosity.

GLACIATION IN THE SKYKOMISH RIVER VALLEY, WASHINGTON

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The Skykomish River, Washington, drains part of the western slopes of the Cascade Mountains and empties into Puget Sound. During the Pleistocene glacial epoch, ice from Canada occupied the Puget Lowland and formed a huge morainal embankment into the Skykomish Valley where it emerges from the Cascade Mountains.

Behind the embankment, a lake occupied the lower 20 miles of the valley, depositing clay on the floor during the latest continental ice advance. The discharge from the lake cut a deep notch in the south rock wall of the valley, but later was withdrawn to a more northerly outlet by a partial washout of the embankment. The resulting cut was rapidly deepened to about 2100 feet, completely draining the lake which lay in the valley.

STRUCTURAL PETROLOGY OF WISSAHICKON SCHIST NEAR PHILADELPHIA, PENNSYLVANIA, WITH SPECIAL REFERENCE TO GRANITIZATION

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This paper is a comparative study of the fabrics of granitized and ungranitized Wissahickon schists near Philadelphia.

Granitization was effected chiefly by the introduction of alkalis and some lime, probably carried in hydrothermal solutions. The mica schists were reconstituted, becoming coarser in grain, with relative increase in feldspars and decrease in micas. A complementary enrichment of less-granitized patches and narrow border zones in iron and magnesia has produced biotite-rich rocks. Hydrothermal activity, following the main period of granitization, has produced some retrograde metamorphism.

Folding in the ungranitized schist is of the flexural slip type. The development of folds can be traced in both mica and quartz fabrics, and the rotation of *S*-surfaces in the fabrics can be correlated with the overturned folds observed in the field. The same features can be identified in the granitized rocks, but less distinctly, since the physical properties of the latter made them react differently from the ungranitized schists during regional metamorphism. Granitization was syntectonic.

Late movements, occurring after the main period of granitization, are recorded locally in the sheared or crushed rocks.

PERMIAN OF NORTHWESTERN WASHINGTON

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In northwestern Washington lenticular Paleozoic limestones associated with argillite, ribbon cherts, and greenstones occur in a northwest-trending belt. The greatest known thickness of the limestone is 200 feet. These rocks have been assigned variously to the Ordovician, Devonian, Carboniferous, and Permian. An investigation of numerous limestone outcrops has yielded Permian fusulinids of "Asiatic" type. *Schubertella*, *Schwagerina*, *Verbeekina*, *Pseudodoliolina*, and *Neoschwagerina* occur in the Twin Lakes limestone deposit near Arlington in Snohomish County, *Schwagerina* and *Neoschwagerina* on Palmer Mountain in King County, *Neoschwagerina* in the Cowell lime-

stone quarry on San Juan Island, and *Yabeina* and *Schwagerina* at Granite Falls in Snohomish County. These appear to represent the latest Permian marine faunas known in the United States.

Among the associated rocks, argillites predominate. Greenstones are abundant in the northern part of the belt but become relatively scarce to the south. Ribbon cherts are present throughout the region. These rocks are lithologically similar to and at least in part the time equivalent of the Cache Creek Group of southern British Columbia.

PACIFIC BASIN AND CONTINENTAL DRIFT

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In Wegner's and Du Toit's versions of "Continental Drift", as well as in Grabau's "Polar Control Theory", the north pole at different times during the Tertiary is postulated as having been in various positions in what is now part of the North Pacific Ocean. Each such position requires a rearrangement of climatic belts from that now in existence, in many cases indicating a colder climate than now for areas around the North Pacific. Examination of the known fossil record indicates, however, that during the Eocene tropical climates extended from at least northern Chile to some place north of 49° N. Lat. along the Pacific Coast, and from about southern Kamchatka to New Zealand along the shores of the Western Pacific. Moreover, several characteristic mollusks of the Pacific Coast early Tertiary, requiring a warm-temperate or subtropical environment, such as *Turritella uvasana, Macrocallista pittsburgensis,* and *Crassatellites washingtoniana,* either occurred in Kamchatka or had close relatives there. All during the Tertiary, the fauna of the Kamchatka area appears to have been closely related to that of the North Pacific Coast, a relationship that would appear to be highly improbable if the north polar area with its cool climates had been in the North Pacific.

The evidence from the marine fossil record around the Pacific Basin strongly militates against any such position of the poles and continents during the Tertiary as would fit the requirements of either Wegner's or Du Toit's "Continental Drift" or Grabau's "Polar Control Theory".

STRIKE-SLIP FAULTING IN THE EASTERN SIERRA NEVADA NEAR BLAIRSDEN, CALIFORNIA

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The Mohawk Valley, Plumas County California, occupies a graben 3 miles wide and 14 miles long which is part of a larger downfaulted area that extends at least 40 miles from Sierra Valley on the southeast probably as far as Indian Creek on the northwest.

Mapping along the southwest border of Mohawk Valley in the Blairsden quadrangle and adjoining areas to the south shows that the nearly horizontal Tertiary volcanics unconformably overlie metamorphic rocks, dipping more than 60° NE., on both sides of the southwest boundary fault.

The boundary fault dips 60°–75° NE. and is downthrown on that side. The dip separation of the base of the Tertiary volcanics is 2500 to 3200 feet. The strike separation of a distinctive black chert member in the metamorphic complex is not less than 18,800 feet.

The data permit calculation of the net slip, with a high degree of probability, to be not less than 17,700 feet, pitching 10.5° NW. in the fault surface. The northeast side of the fault has moved northwest relative to the southwest side.

In the nomenclature of Mason L. Hill, the fault is a left lateral normal fault. Since the strike-slip component of not less than 17,300 feet is approximately 5 times as great as the dip-slip component, the fault may be characterized in more familiar terminology as a strike-slip fault.

COMPACTION OF MARINE SEDIMENTS

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Cores from the bottoms of the basins off southern California present a variation of water content that is a function of both sediment grain size and depth of burial. The decrease of water content with depth is controlled by the rate of sediment deposition and the permeability. The rate of deposition

is a measure of the loading, and the higher the rate, the faster water is squeezed out of the sediments. The permeability limits the rate of outflow of the interstitial water. Knowing the rate of deposition and the shape of the water-content depth curve, one may compute the permeability and the volume of water that has been discharged vertically upward through the sediment. From these data one may determine the time required for the basins to become filled with sediment, assuming constant conditions in the future. Important diagenetic changes in the sediment probably result from the passage of large quantities of water through depth zones of differing organic content and pH.

SOILS AS A KEY IN GEOLOGIC MAPPING

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Soils may be of great assistance to geologic mapping in well-mantled districts of markedly divergent bedrock types. Their stage of development is an aid in separating and mapping Quaternary and late Tertiary alluvial sequences, especially in cases of essentially identical composition and texture of the parent detritus. Examples from the San Joaquin Valley of California are discussed.

PALISADES DIABASE JOINT CRACKS

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In New Jersey, opposite 125 Street in New York, a road cut exposes a cross section of the lower part of the noted sill, showing the chilled basal zone of normal diabase, the olivine-rich zone, and the overlying olivine-poor phase. In contrast with the other zones, the olivine diabase is highly altered and easily weathered except for narrow selvages of resistant rock adjacent to the vertical joint cracks. The relationship of these thin bands appears to be identical to that observed by the author locally in the Steens Mountain olivine basalt of southeastern Oregon, where evidence proved that the escape of volatiles up the normal contraction cracks permitted the immediately adjacent lava to crystallize without the deuteric alteration of the olivine. Various features also resemble the structures described by Mackin in the Iron Springs district of southwestern Utah.

GRANITIZATION IN THE CENTRAL OKANOGAN RANGE, OKANOGAN COUNTY, WASHINGTON

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Regionally metamorphosed and partially granitized Paleozoic rocks near Riverside and Conconully continue northwestward to become part of the granodioritic complex of the Okanogan Range. Soda metasomatism during the latter part of regional metamorphism was followed by potash metasomatism. These processes comprised an earlier synkinematic phase and a later static phase.

Amphibolites, sediment-derived hornblende-diopside granulites, and quartzites have preserved their identities for tens of miles along the tectonic trend. Intercalated, more argillaceous types are represented by biotite schists and hornblende-biotite schists. Most of these rocks, with preference for the more argillaceous types, have been transformed into augen, flaser, and banded gneisses, and gneissose and directionless rocks of dioritic, tonalitic, and granodioritic composition. All transitions occur between the original and the metasomatized rocks.

These rocks exhibit a definite sequence of mineralogical and textural changes. Plagioclase increases in size with enrichment in soda. Mafics show a history of aggregation and consolidation enclosing groundmass minerals, but in the late stages, with the coarse development of quartz and feldspar, they are frequently attacked and often relegated to an intergranular position. The beginning of introduction of potassium is marked by biotitization of the hornblende. Microcline first appears in the intergranular, replacing plagioclase, and later develops into large porphyroblasts which enclose all earlier minerals. Textures remain crystalloblastic throughout, although in the final stage they appear hypidiomorphic granular. Relics which show less-advanced stages of transformation occur as bands, patches, or schlierenlike streaks in the more strongly transformed rocks.

ORDOVICIAN STRATIGRAPHY FROM CENTRAL UTAH TO CENTRAL NEVADA

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Stratigraphy of the Ordovician Pogonip-Eureka sequence is considered from near Scipio, central Utah, to the Antelope Range, central Nevada, 300 miles to the west. Pogonip limestone thickens from about 1700 feet in the east near the miogeosynclinal margin to a rather constant 3000 feet in western Utah and eastern Nevada, the broad area of the miogeosyncline having subsided as a plate. Texture of included siliceous detritus decreases westward. Lithologic units and 12 Canadian and probable early Chazyan faunal zones are recognized and defined, beginning with the basal *Symphysurina-Nanorthis* zone. The interval between the top of the Pogonip limestone and the top of the Eureka quartzite decreases from about 900 feet in western Utah to some 500 feet in eastern Nevada, then increases to 900 feet in the Antelope Range. In this sequence the lower (Swan Peak) quartzite, 350 feet in central Utah, is regressive, thinning in western Utah to disappear in eastern Nevada, grading into successively younger Pogonip zones westward. The upper (Eureka) quartzite, overlying a dolomite unit of less than 100 feet, thins from more than 500 feet in western Utah to 150 to 400 feet in Nevada. A lower quartzite reappears in the Antelope Range, separated from the overlying typical Eureka quartzite by a 700-foot calcareous shale sequence with late Chazyan to medial Trentonian faunas. The succeeding carbonate rocks, late Trentonian, Cincinnatian, or both, become argillaceous on the west.

FOUNDATION GEOLOGY AT PINE FLAT DAM, KINGS RIVER, CALIFORNIA

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Pine Flat dam is being built on Kings River about 30 miles east of Fresno, California. It will be a concrete gravity type, 440 feet in height, with an overflow spillway. The site has been investigated intermittently since 1922. Construction started in 1947 and is scheduled for completion in 1954.

The regional geology is typical of the Sierra Nevada foothills, with metamorphosed sedimentary and igneous rocks intruded by basic to acidic igneous rocks. The dam will be founded largely upon plagioclase amphibolite derived from basic lavas. Diorite occurs beneath the extreme south end of the dam. The amphibolite is cut by numerous dikes of metadiabase, microdiorite, porphyritic diorite, and aplite, and by veinlets of quartz, potash feldspar, calcite, and zeolites. The amphibolite everywhere shows low-grade dynamic metamorphism, with contact metamorphism near the contact with diorite. Hydrothermal alteration has seriously affected many of the dike rocks, and to a lesser extent the amphibolite adjacent thereto and in shattered zones. Schistosity and fracture cleavage are poorly developed, but jointing is severe, and small faults and shatter zones are common. Weathering has been severe, especially on the north abutment, and is deepest in the shatter zones and within the dikes.

The structural features do not seriously weaken the rock, and the foundation is thoroughly competent to support the load and to withstand the stresses to which it will be subjected. The severe jointing extends the grouting requirements but improves the drainage.

COMPOSITION AND QUALITY OF THE "BLACK GRANITE" DIMENSION STONE OF SAN DIEGO COUNTY, CALIFORNIA

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"Black Granite" quarries in San Diego County have been operated almost wholly in residual boulder deposits of gabbroic rocks. The "black granite" includes such petrographic varieties as hornblende gabbro, norite, and quartz-biotite gabbro. The homogeneous color and texture characteristic of the "black granite" are locally interrupted by inclusions, spots, and coarse clots. Some veinlike masses contain minerals formed during a period of hydrothermal activity and are so numerous in some places that the rock is rendered unfit for use.

Two distinct joint sets, a less definite sheeting, and irregularly distributed fractures are present.

Steeply dipping faults are exposed in some of the quarries. Rift and grain directions are obscure, but where present appear to parallel joint and sheeting surfaces.

The residual boulders have been formed chiefly by expansion and subsequent breaking apart of the rock, caused in large part by the oxidation and hydration of the ferrous iron in the ferro-magnesian minerals and in the iron sulphides. The thickness of the weathered rock ranges from a few inches to scores on even hundreds of feet and is related in part to the distribution and extent of old erosion surfaces.

Objectional staining of monuments in San Diego cemeteries has been accelerated by sprinkling. White coatings have been formed on all types of stones by the evaporation of hard water and subsequent deposition of the dissolved solids.

TILL ISOPLETH MAP OF NORTHEASTERN MONTANA AND NORTHWESTERN NORTH DAKOTA*

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The limestone-dolomite pebble content of the surface tills of an area of about 12,000 square miles in northeastern Montana and northwestern North Dakota has been represented on an isopleth map, which shows the areal distribution of a variable by means of isopleths or lines of equal magnitude. The map is based on 64 pebble counts, and the successive isopleths indicate changes of 10 per cent in the limestone-dolomite content. The tills are relatively unweathered and contain unaltered limestone and dolomite pebbles throughout their vertical extent.

The greater part of the isopleth map resembles an undulating plateau in which the number of limestone-dolomite pebbles ranges between approximately 50 and 80 per cent of the foreign pebble content of the till. In northwestern North Dakota, however, a sharply defined lobate area shows limestone-dolomite percentages as low as 27 per cent. The decrease in limestone-dolomite is accompanied by an increase in granitic rocks and in metamorphic foliates. The contrasting lithology of the till in this area has assisted in the recognition of a drift of limited extent in northwestern North Dakota.

The belt of Paleozoic limestones and dolomites bordering the Canadian Shield to the northeast varies in width up to more than 100 miles. The variations in limestone-dolomite content of the drift of northwestern North Dakota may thus be due to differences in the direction of ice advance across this variable belt. The alternative possibility of a consistent direction of advance but with alternate burial and exposure of the limestone-dolomite areas cannot now be evaluated.

ALLANITE FROM YOSEMITE NATIONAL PARK AND FIORDLAND, NEW ZEALAND

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The occurrence, composition, and physical properties of allanite from three occurrences, two from Yosemite National Park, California, and one from Wilmot Pass, Fiordland, New Zealand, are described. Refractive indices are high ranging from $\alpha = 1.763$–1.791; $\gamma = 1.788$–1.821, whereas 2 V is relatively small in all instances, *viz.* 45° and 60° for Yosemite material and 57° for the New Zealand mineral; the sign is negative in the first two instances but positive in the latter. Density, relative solubility in acids, degree of metamictization, and possible age are discussed.

RETARDATION METHOD FOR DETERMINING THE ORIENTATION OF UNIAXIAL CRYSTALS

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The "retardation method" is described for determining the orientation of *c* axes of uniaxial crystals without the use of the universal stage.

1. The vertical plane which contains the *c* axis is found from the vibration direction of the extraordinary ray (slow ray for quartz).

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2. The inclination of the *c* axis can be calculated from the retardation measure with a Berek compensator. For this purpose the thin section should be of a known and uniform thickness if the method is to be accurate.
3. The direction of plunge of the *c* axis is determined from a study of the interference figure.

The working time at microscope is comparable with that needed for the universal stage, and errors in calculating orientation are shown to be of the same order of magnitude as those made with the universal stage. The retardation method appears the more accurate one for grains whose *c* axes are nearly perpendicular to the thin section. Quartz-fabric diagrams of the same thin sections have been made by both methods and are given as illustrations.

GEOLOGICAL INVESTIGATIONS AND PROBLEMS—FOLSOM DAM PROJECT, CALIFORNIA*

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The Folsom Dam project comprises an overpour concrete gravity section with earthfill wing dams on the American River, an auxiliary dam across a Pleistocene channel, and eight saddle embankments. Totalling 4.6 miles in length, these structures will form the world's fourth largest mass dam.

Quartz diorite underlies the main dam and seven saddle embankments. Joints are abundant and commonly are closely spaced in wide zones which have weathered irregularly and thoroughly to depths as great as 85 feet. Schistose rocks of the Jurassic Amador group(?) underlie the auxiliary dam and one embankment. Miocene (Mehrten formation) andesitic gravels cap ridges between structures and occur in one embankment foundation.

Geological interpretation was used to anticipate the amount of dental treatment of the deeply weathered zones, the extent and volume of hydraulic mining debris 65 feet deep in the main channel, and of dredged Pleistocene gravels up to 80 feet thick which fill an ancestral channel of the American River.

Geologic data aided in the selection of damsites and two tunnel alignments and in location of adequate construction materials. Reservoir tightness, landslide hazards, detailed foundation characters, and estimated excavation depths and quantities were established.

PHYSICAL CHEMISTRY OF QUICKSILVER DEPOSITION

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Recently published thermodynamic data on hydrogen sulfide and the compounds of mercury permit an evaluation of possible methods of transport of mercury by ore solutions. The extreme insolubility of mercuric sulfide in water can be modified by the formation of complex ions, but of the various possible ones only the complex sulfide ion can give appreciable solubility. If sufficient dissolved sulfur is present, significant amounts of mercury may be held in solution at any value of the pH above 8. The solubility at high temperatures is not significantly increased by the diminished solubility of H_2S, by change in the ionization constant of H_2S, or by shifts in equilibrium reactions involving H_2S and other gases. Mercuric chloride is sufficiently volatile so that significant amounts of mercury could be carried in a gas phase even at temperatures as low as 100° C., but if a liquid phase is present also the chloride would dissolve and mercuric sulfide would precipitate. Vapor-pressure measurements and spectrographic data indicate that mercuric sulfide on vaporization breaks down into its elements; this means that mercury can be transported as the vapor of the native metal, and that cinnabar cannot exist in the presence of a moving vein fluid at temperatures above about 250° C. In summary, thermodynamic considerations suggest that the two most important means of transport in the formation of quicksilver deposits are transport as the native metal in the vapor phase and as the complex sulfide ion in solution.

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FELDSPATHIZED SCHIST OF THE FOURMILE AREA, CUSTER COUNTY, SOUTH DAKOTA*

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In the southern part of the Black Hills, South Dakota, a large number of pegmatite dikes are found in the Precambrian metamorphic rocks. Not uncommonly the schist wall rock has been altered by the introduction of pegmatite materials forming a thin shell of fine-grained granulite at the pegmatite and schist contact.

Within the Fourmile area many of these dikes are surrounded by a zone, up to 2 feet in width, of feldspathized schist containing abundant large porphyroblasts of microcline and oligoclase.

The altered wall rock grades on the one hand into the quartz-mica schist country rock and ends abruptly along a sharp contact with the pegmatite. The feldspathized wall rock consists of quartz, biotite, and muscovite, inherited from the schist, together with new microcline, oligoclase, tourmaline, and apatite. Field relations and microscopic features indicate that the feldspathized schist was formed in place by partial recrystallization of schist which was associated with introduction of materials from pegmatite solutions. These solutions permeated the quartz-mica schist country rock and reacted with quartz and alumina-excess biotite and muscovite to form tourmaline, apatite, and alkali feldspar.

The process probably took place before and during the crystallization of the marginal part of the pegmatite dikes, and ceased before the main part of the pegmatite crystallized.

MINERALOGY AND PETROLOGY OF THE QUIEN SABE VOLCANICS, CALIFORNIA

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The Middle (?) Miocene Quien Sabe volcanics form the crest of a portion of the Diablo Range of the central Coast Ranges of California, 90 miles southeast of San Francisco; they are more than 4000 feet thick and include andesitic agglomerate, andesite, basalt and olivine basalt flows, and intrusive andesite, with less abundant dacite flows, intrusive rhyolite, and tuffaceous sandstone. The rhyolite is irruptive into the other rocks of the assemblage.

The agglomerate is composed of andesite fragments, crystal fragments, and glass shards. The extrusive andesite contains phenocrysts of zoned plagioclase, oxyhornblende, hypersthene, augite, and biotite, in a hyalopilitic groundmass of feldspar microlites and glass. Chloritization of biotite is common, and many oxyhornblende crystals are pseudomorphed by iron ore. Presence of green-brown hornblende in place of oxyhornblende in the intrusive andesite suggests a lower consolidation temperature for the intrusive masses than for the flows. Phenocrysts in the basalt are augite and saussuritized plagioclase; the olivine of the olivine basalt is phenocrystic or is a constituent of the groundmass. Dacite is limited in occurrence and contains scattered phenocrysts of quartz and plagioclase, the latter almost completely pseudomorphed by coarsely crystalline calcite. Rhyolite forms two plugs and contains small, widely scattered phenocrysts of oligoclase, quartz, and altered biotite, enclosed within a glassy, opaline groundmass in which are scattered microlites of orthoclase. Baueritization of biotite and opalization of the groundmass are indications of hydrothermal alteration of the rhyolite.

Chemical and micrometric analyses are compared with those of similar rocks reported from other areas.

CLAY FOUNDATION PROBLEM, FRIANT-KERN CANAL, CALIFORNIA

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The Friant-Kern Canal, now under construction by the U. S. Bureau of Reclamation, is built 18 miles in Tulare County, California, in Quaternary colluvial clays, designated the "Porterville

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clays." The clays are montmorillonitic and have swelled enough, locally, to disturb the concrete lining of the canal.

The Porterville clays occupy a half-mile wide concave transition slope between the San Joaquin Valley and the Sierra Nevada foothills. They are reddish-brown, plastic, calcareous, and relatively impermeable. The predominating colloid, according to x-ray analysis, is calcium beidellite. A sand and gravel fraction, including gabbro-diorite and various metamorphic rocks rich in calcic feldspar, is characteristically abundant. From such lithologies the Porterville clay has been derived by weathering.

Efforts to forestall cracking, such as has already developed in one section of the canal, have included use of 2 to 8 feet of compacted earth backfill, in place of concrete lining, against permeable horizons and in embankments, and elsewhere, use of an asphalt membrane between the subgrade and a 3-inch unreinforced concrete lining. Limited operations in the summer of 1949 resulted in negligible bank erosion and seepage loss in the earth-lined stretches. Efficacy of the asphalt sublinings cannot yet be evaluated.

EARLY TERTIARY WELDED TUFFS IN THE IRON SPRINGS DISTRICT, UTAH*

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The Iron Springs district is located in the Basin-Range province just west of the Hurricane fault zone in southwestern Utah. Sedimentary rocks of Jurassic, Cretaceous, and Eocene age dip outward from three laccolithic intrusions. Latitic volcanic rocks form the outermost rings of the target patterns around the intrusions. They correspond closely in chemical and mineralogical composition with the monzonitic intrusive rocks. The volcanic sequence was spread out on the surface just prior to emplacement of the intrusions.

The volcanic sequence includes six distinct units, with an overall thickness of about 1200 feet. Units 1 and 5 (from the base upward) are crystal-type biotite tuffs in part moderately welded. Unit 2 is a latite flow which covered unit 1, except locally, before the next burst. Units 3 and 6 are glassy tuffs with small irregular fragments of other volcanic rocks. These units are strongly welded near the base. Unit 3 differs from the other units in that it is a glass, strongly foliated, and readily mistakable for a flow. It was probably formed from a burst of dust which was hot enough to weld itself throughout.

These units rest conformably on an Eocene (Pink Cliffs Wasatch) depositional floor, and Wasatch type sediments are interbedded in the upper part of the sequence. Units 3, 4, 5, and 6 occur throughout the district with remarkably uniform thickness. The source is unknown, but these rocks evidently represent repeated early Tertiary volcanic explosions of enormous magnitude.

RATE AND PROCESSES OF ENLARGEMENT OF ROAD CUTS IN BOULDERY ALLUVIUM

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A series of road cuts in bouldery alluvium have been under observation for a period of 50 years (1899–1949) and have been closely studied at frequent intervals for the past 5 years. Photographs of the area taken 50 years apart plus a comparison of detailed topographic surveys show that the initial scarps have widened both laterally and upslope until they are now 10 times their original size, the enlargement resulting from various natural processes of mass wasting.

The rim of a typical cut has retreated upslope a total distance of 74 feet in the 50-year period, or at an average rate of 1.48 feet per year. Profiles of the cuts show that the upper part of the scarp remains raw and oversteepened with slope angles between 50° and 60° as compared with 31° for the undisturbed slope above the cut. The knickpoint or rim retains its sharpness and abrupt change in slope from the more gentle slope above to the much steeper slope of the upper part of the bank below. The knickpoint appears to migrate up the slope without change in form and evidently will not be effaced until the top of the entire gravel bank is reached.

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Enlargement is not the result of mass slumping but is due to the combined effects of raveling by frost wedging, impact and ploughing by dislodged cobbles, wind action, beating of rain and hail, and sheet and rill erosion.

PHYSICAL FEATURES OF THE LIGHTNING LAKES VALLEY, SOUTHWESTERN BRITISH COLUMBIA

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The physical features of the Lightning Lakes Valley—notably a V-shaped cross section and overdeepening with respect to glaciated tributary valleys in its western part and the presence of outwash deposits in its eastern part—show that the valley was occupied by a major late Pleistocene ice-diverted stream which flowed westward through the Cascade Mountains. This evidence indicates, in turn, that the Cordilleran ice sheet had virtually disappeared from the valleys of the Cascade Mountains at a time when it still effectively blocked the valleys of the adjacent Interior Plateau. Aggradation of the Lightning Lakes Valley has taken place in postglacial time with the creation of a chain of lakes, dammed either by fans built by tributary streams or by talus and avalanches fallen from the oversteepened walls.

STRUCTURE IN THE VOLCANIC ROCKS OF THE OLYMPIC PENINSULA, WASHINGTON*

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The volcanic rocks of the Olympic Peninsula form a prominent horseshoe-shaped exposure around the northern, eastern, and southern borders of the Peninsula. These rocks are called the Metchosin volcanics by Weaver, who correlates them with the Metchosin volcanics of middle Eocene age on Vancouver Island. They are underlain by the Solduc formation of Weaver and overlain by younger fossiliferous sedimentary beds.

The structure of the Peninsula has been described as anticlinal, a conclusion based upon the following evidence: (1) the outcrop pattern suggests an anticline plunging to the east; (2) the tops of the volcanic rocks are everywhere toward the outside of the Peninsula; and (3) the Solduc formation below the volcanic rocks is more highly deformed and metamorphosed than the volcanics or overlying sedimentary materials. Two facts, however, do not fit into the anticlinal hypothesis: (1) fossils of Oligocene age were found by Walter Warren in rocks below the Metchosin volcanics, and (2) the tremendous apparent thickness of 120,000 feet of the section along the Dosewallips river from Hood Canal to the top of Mount Claywood, compared to an estimated average thickness of less than a quarter of this, is greater than can be explained by ordinary processes. It is concluded that the structure of the Peninsula is not a simple anticline and that the rocks which have been called the Solduc formation include materials of Oligocene and possibly younger age. The great apparent thickness and the complexity result from steeply dipping thrust faults distributed through the phyllites and argillites of the Solduc formation. The forces which have caused the faulting have also caused buckling along the contact with the competent lavas.

RIO VISTA, CALIFORNIA, FAULT SCARP

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The eastern margin of the Montezuma Hills, south of Rio Vista, California, is for about 2½ miles a steep bluff facing the flat valley of the lower Sacramento River. The bluff trends S. 19°–22° W., is remarkably straight, and cuts across flatly east-dipping continental Pleistocene sediments of the Montezuma formation. Its fault scarp nature has been recently established by coring a number of 90–160 foot drill holes. The evidence includes abrupt change of section across, but not along, the line of the scarp. East of the scarp, 40–55 feet of dredged fill, comprising clean, loose, coarse sand rests on

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carbonaceous silt and clay, with associated peat. This floodplain (not channel) deposit thins rapidly toward the scarp and is underlain by the Montezuma beds.

The fault dip is steep; its direction is unknown. The height of the scarp before emplacement of the dredged fill was about 100 feet. Remnants of a bench 40 feet below its brow suggest two-stage uplift. Records do not suggest displacement during historic times. The Rio Vista fault is possibly an incident in the continuing rise of the Rio Vista dome.

A similar but west-facing scarp bounds the Montezuma Hills for 3 miles on the southwest. Its line, produced, narrowly misses Collinsville and passes through Antioch, both of which were severely damaged by a quake in 1889.

TRIASSIC STRATIGRAPHY IN THE CENTRAL WASATCH MOUNTAINS, UTAH

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The Triassic sequence in the central Wasatch is well exposed in the vicinity of Parley's and Red Butte canyons near Salt Lake City. The following litho-stratigraphic units are recognized: (1) Woodside shale, 410 feet of remarkably uniform, red silty shale; (2) Thaynes formation, 2650 feet of gray to pale-brown, fossiliferous limestones, shaley limestones, shales, and calcareous sandstones, with the *Meekoceras* zone near the base; (3) Timothy formation, 1310 feet of red shales and siltstones, with interbedded reddish-purple and reddish-brown sandstones; (4) Shinarump conglomerate, 90 feet of siliceous quartz sandstone with lenses of pebble conglomerate; (5) Chinle formation, 530 feet of dusky red shales, red siltstones, and reddish-brown sandstones.

The central Wasatch Timothy facies is more argillaceous and silty and is somewhat redder than the type Timothy sandstone in southeastern Idaho. An intermediate facies is exposed in Weber Canyon near Devil's Slide, Utah.

The Thaynes formation thins and disappears to the east and southeast where the underlying Woodside and overlying Timothy join to constitute the Moenkopi formation. Thus the combined Woodside, Thaynes, and Timothy are recognized as constituting the Moenkopi group, since they occupy a common stratigraphic interval and since the Woodside and Timothy are lithologically similar to the Moenkopi formation.

JORDISITE AND ILSEMANNITE

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Ilsemannite from Clackamas County, Oregon, occurs as a secondary mineral coating a fine-grained, black, submetallic material. Chemical analyses of the latter prove it to be molybdenum disulfide. X-ray powder diffraction patterns show a lack of all molybdenite lines and indicate that the material is amorphous. Cornu, in a note on material from Freiberg, Germany (1909), suggested the possibility of a colloidal MoS_2 and named it jordisite without adequately describing it. The present work confirms the existence of such a substance.

The scarcity of ilsemannite in molybdenite areas may be due to the fact that molybdenite is not easily altered. Jordisite, owing to its amorphous state, is more readily altered and is probably the source of most ilsemannite.

MINERAL DEPOSITS CONTAINING URANIUM IN BRITISH COLUMBIA*

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Where uranium-bearing veins have been found in British Columbia, the uranium mineral is the crystalline variety of uranium oxide, uraninite, rather than the amorphous colloform variety, pitchblende, that is found in the Great Bear Lake deposit and in occurrences of similar type elsewhere in the Precambrian shield. The British Columbia uraninite is not found in granite pegmatites such as the occurrences in eastern North America but rather in gold-bearing metallic veins. In these veins, the uraninite is associated with cobalt-nickel sulpharsenides similar to those found in normal meso-

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thermal pitchblende deposits, but the other associated metallic minerals, arsenopyrite and molybdenite, and the gangue minerals, hornblende, feldspar, apatite, scheelite, and allanite, indicate that the veins are hypothermal rather than mesothermal. This type of mineralization seems to be characteristic of Cordilleran mineral deposits that contain uranium.

ENGINEERING GEOLOGY OF SAN FRANCISCO BAY

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The geological engineering problems of San Francisco Bay involve six main subjects: (1) rock foundations for bridges and cable anchorages; (2) sediment foundations for bridges and tube segments for under-water tunnels; (3) length of piles for bridge and building supports; (4) stability of side slopes of excavations and embankments; (5) settlement due to imposed loads, such as earth fill for causeways; and (6) source of sand for earth fills.

The sediments in San Francisco Bay consist of a sequence of clay, sand, and gravel beds, mainly of Quaternary age, resting upon weathered Franciscan rocks of considerable relief. The most recent formation is a sequence of soft clay, silt, and sand, 1 to 80 feet thick, deposited upon sands presumably largely of eolian origin, which in turn rest upon an eroded surface cut on late Quaternary sand and clay. Most of the engineering problems outlined above depend for their answer upon the strength and thickness of these soft sediments. The underlying deposits in general have adequate strength. The sand used for filling operations comes mainly from the sediments of wind-blown origin in places where the overlying soft layer is thin.

VOLCANIC ASH DEPOSITS OF THE FRIANT FORMATION, FRESNO AND MADERA COUNTIES, CALIFORNIA

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The Friant formation, of probable Pleistocene age, occurs in dissected terraces in the foothill embayments adjacent to the San Joaquin River where it emerges from the Sierra Nevada. The formation is composed of fluviatile and lacustrine deposits of silt, sand, gravel, and volcanic ash. Locally the ash comprises pure, finely laminated deposits up to 150 feet thick.

Individual lamina generally show a textural gradation upward from coarse to fine and commonly have an iron-oxide stain. The ash consists almost entirely of clear glass fragments having a roughly equidimensional shape. Diameters range from 0.001 to 0.015 mm. The material has an average index of refraction of 1.5060 which indicates a rhyolitic or andesitic type of composition.

Massive, pure, laminated deposits of ash in the Friant formation occur at low levels in downstream segments of tributaries to the San Joaquin River near Friant. The San Joaquin River, prior to its Recent entrenchment, aggraded its bed above the level of these tributaries and impounded the drainage. Into the lakes thus formed the river overflowed periodically and carried large quantities of volcanic ash. The individual lamina are believed to represent the separate overflows of the river. These floods may have been the result of diurnal fluctuations in river discharge during periods of high runoff.

No rhyolitic or andesitic eruptions of late Tertiary or Pleistocene age are known to have occurred within the drainage basin of the San Joaquin River and its tributaries. Probably the ash was derived from late Pleistocene eruptions of such material from the Mono Craters area, across the divide east of the headwaters of the San Joaquin River.

FOUNDATION PROBLEMS AT DAMS OF THE MERCED COUNTY STREAM GROUP*

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The Corps of Engineers has built three earthfill dams for flood control across Mariposa, Owens, and Burns creeks and is authorized to build a fourth across Bear Creek in the area east of Merced,

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California. The dams range from 60 to 93 feet high with uncontrolled outlets and ungated spillways. The design is such as will reduce flood flows to safe channel capacities downstream. Three of the dams are founded on pre-Cretaceous, steeply dipping metamorphic rocks that are intruded by granitic dikes, with the development of migmatized or granitized zones. These rocks are weathered to a maximum depth of 30 feet, but the weathered rock is relatively impervious. The fourth dam is founded on rhyolitic tuffaceous sands and clays of the Valley Springs formation. This formation is relatively impervious, has good bearing strength, but has little resistance to erosion. The foundation areas were stripped to a depth of about 12 inches, principally to remove organic material, and the core trench was excavated approximately 5 feet into weathered rock. Three of the spillways are unlined, the fourth at Burns Dam is protected by a short concrete slab. The spillways probably will carry water only at rare intervals.

SOME QUESTIONS BEARING ON THE GRANITE PROBLEM

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As a basis for discussion on the origin and mode of emplacement of bodies of granitic rocks, the following proposition is stated: That certain of the most characteristic and widespread chemical, petrographic, and structural features of granite and granodiorite are more compatible with origin by intrusion of magma than with origin by granitization (metasomatism) in place; provided that the term magma is used to include all naturally occurring mobile rock matter that consists in noteworthy part of a liquid phase having the composition of a silicate melt.

DIFFUSION RATES IN QUARTZ

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Ions of various metals have been made to diffuse through quartz in an electrical field of about 1000 volts/cm. Rates of diffusion may be determined from measurements of the electrical conductivity of the sample and its variation with time. Preliminary results are given for the diffusion of Li, Na, K, Fe, Mg, Ag parallel to the *c* axis of quartz at 500°C.

PHYSIOGRAPHIC HISTORY OF SOUTHERN ALASKA: A HYPOTHESIS*

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A hypothesis for the physiographic history of southern Alaska is proposed to explain the anomalous courses of large rivers across plains and mountains, rádial drainage from the Copper River plateau, isolated mountains of great height, and large areas of drainage adjusted to structure. The hypothesis is based on: (1) the distribution of poorly consolidated Tertiary rocks, which coincides largely with lowlands; (2) evidence of superposed drainage; and (3) evidence of crustal warping and dislocation, such as deformed glacial terraces, deep Quaternary fill of some lowlands, and recent faulting.

The physiographic history includes:

(1) Accumulation of discontinuous cover of early Tertiary continental sediments on a post-mature surface.

(2) Middle Tertiary orogeny, folding and faulting of Tertiary rocks, and contemporaneous deposition of several thousand feet of gravel in subsiding basins.

(3) Development of a lowland on all Alaska except strongly uplifted areas. Over hard pre-Tertiary rocks, drainage became well adjusted to structure. Over Tertiary rocks the lowland was a nearly featureless plain, on which structure had little effect on drainage.

(4) Warping and minor faulting in late Tertiary and Quaternary time, controlling development of the drainage pattern. Major streams follow troughs of this deformation, and their tributaries are consequent upon the slopes of these troughs where Tertiary rocks were at the surface when deformation started. Where pre-Tertiary rocks were at the surface when deformation started, the new erosion cycle inherited well-adjusted drainage from the earlier cycle.

(5) Modification of topographic detail by glaciation and periglacial processes.

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GEOMETRY OF SHEARING STRESS AND RELATION TO FAULTING

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Although no present theory of rupture is entirely satisfactory, the geometry of shearing stress supplies a useful basis for the analysis of faulting.

The three-dimensional distribution of shearing-stress intensities and the orientation of resolved shearing stress for different stress systems are plotted on stereographic nets. By use of such diagrams the relationship of fault systems to stress systems is more apparent, and many interpretations regarding faults are possible. For example, it is possible to relate orientation of net slip to orientation of resolved shearing stress.

Factors of anisotropism of rocks and the discrepancy between orientation of shear rupture and orientation of maximum shearing stress are considered.

IMPROVED DITHIZONE FIELD TEST FOR HEAVY METALS IN WATER

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In many areas of the Pacific Northwest heavy runoff from rain, melting snow, and ice fields causes extreme dilution of the heavy-metal content of natural waters.

Field work has shown that in many areas it is practical to apply geochemical methods in the search for copper and zinc only if it is feasible to detect as little as 0.001 parts per million of these metals in natural waters.

A modification of the dithizone methods has been developed. This modified method is simple, as accurate as is necessary for field work, and can readily detect heavy metals in concentrations as low as 0.001 p.p.m. Under favorable conditions an experienced field man can detect even lower concentrations.

MULTIPLE DIKE FEEDERS OF THE COLUMBIA RIVER BASALT

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The concept of fissure eruption of the plateau basalts is generally accepted, but some writers have expressed skepticism of this mode of eruption because the actual connection of a dike with a surface flow is seldom seen. It must be rare, however, for a dike and flow to remain connected throughout the entire period of solidification. Withdrawal of magma down the dike, or extrusion of new lava to the surface will break the connection.

Several large dikes cut flows of the Columbia River basalt in northeastern Oregon. Some of these dikes are almost continuously exposed through a vertical range of as much as 4000 feet on the steep canyon walls of this region. Each dike studied in detail shows evidence of having fed from one to six separate flows, but in only one example was an unbroken connection between flow and dike maintained during solidification. Among features indicating a former connection, however, are: (1) thin selvages on one or both sides of the dike that flare out and connect with the base of a flow, although the central part of the dike crosscuts the flow, (2) abrupt changes in the columnar jointing of the flow adjacent to the dike, (3) slumping of the flow toward the dike, (4) small ridges of scoriaceous breccia heaped on the flow immediately adjacent to the dike, and (5) marked changes in vesicularity, jointing, or in the number of multiple components within the dike as it approaches certain flows.

PREHNITIZATION OF ALBITITE

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A steeply dipping albitite dike, 20–30 feet wide, which cuts serpentine is exposed in a quarry about half a mile northwest of Haylmore in the Bridge River area, southwestern British Columbia. Prehnite has replaced part of the dike, especially its footwall where a conspicuous white layer about 3 feet wide consisting mainly of prehnite has been formed. A comparison of the chemical analysis of this highly altered rock from the footwall (68% prehnite, 31% diopside, 1% epidote and quartz) with that of

slightly altered rock from the center of the dike (77% albite, 15% prehnite, 3% quartz, 4% chlorite, 1% epidote etc.) shows principally an increase from 6.32 to 26.34% CaO and decreases from 4.93 to 0.09% Na_2O and 57.38 to 44.84% SiO_2. A hypothesis that this metasomatism has been caused by fluids containing lime yielded by the serpentinization of peridotite is considered.

SOURCES OF HEAT AND WATER SUPPLY OF THERMAL SPRINGS, WITH PARTICULAR REFERENCE TO STEAMBOAT SPRINGS, NEVADA*

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Thermal springs are classified as: A. Nonvolcanic; heat and water supply are not immediately related to volcanism. B. Intermediate; excess heat is due to abnormally high geothermal gradients resulting from volcanism, but the water is entirely meteoric. C. Volcanic; excess heat, much of the mineral content and part of the water are from a volcanic source.

Lines of evidence indicating the origin of a thermal-spring system are: 1.Temperature relations, including surface temperatures of springs, geothermal gradients and heat inventory of the spring system, and possible sources of excess heat. 2. Mineral content of the thermal water and its possible sources, with attention focused on the more soluble components that are seldom deposited in veins. Chlorine, boron, and to a lesser extent sulfur and carbon dioxide in their various chemical combinations are critical indicators, particularly when considered together. 3. Composition of associated gases. 4. Variations in spring discharges and water levels, as related to variations in meteoric water supply. 5. Isotopic composition of spring and meteoric waters. 6. Regional and local geology, and in particular the age and extent of any volcanic rocks.

These lines of evidence, when applied to Steamboat Springs and evaluated, definitely indicate a volcanic origin.

In the Steamboat Springs system, meteoric water migrates downward and toward the core of the system, with stratigraphic and structural control, and mixes with rising volcanic water. This migration is due to differences in density related largely to temperature; artesian conditions are not essential.

WELDED TUFF MEMBER OF THE RATTLESNAKE FORMATION

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A feature of the Rattlesnake formation is a layer of welded tuff which has been called a rhyolite flow. This layer stands in cliffs 50 to 75 feet in height and extends from the type locality near Picture Gorge eastward along both sides of the John Day River valley to the vicinity of John Day, Oregon. It is composed of pumice lapilli scattered through a matrix of vitric tuff and could properly be called an ignimbrite.

EFFECTS OF GRAIN ELONGATION ON FABRIC DIAGRAMS

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In most cases a fabric diagram presents a systematically distorted picture. This distortion comes from the plots on a point diagram that represent crystals whose centers lie outside the thin section. As the distance of the centers from the thin section increases, the grains that extend into the thin section become restricted to those whose long dimension is nearly normal to the section. A diagram of the long axes of acicular crystals of any degree of preferred orientation is deformed by a tendency of the points to concentrate near the center of the diagram, whereas the diagrams of normals to mica flakes, as Turner and others have noted, tend to show a girdle pattern.

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A fabric diagram free from systematic distortion due to grain shape may be constructed by allowing for the areas of the grains plotted.

Formulas are derived which give the effects of elongation and grain shape for a population of crystal grains of random orientation, whose centers are randomly distributed through a homogeneous rock. If the grains approximate the shape of ellipsoids of revolution, the measured grain direction being parallel to the axis of revolution, the formula

$$P = K \sin\alpha \sqrt{e^2 \cos^2\alpha + \sin^2\alpha}$$

gives the density contour profile of all crystals of elongation e, with the axis of revolution inclined at an angle α to the thin section. The quantity K is a probability constant.

PACIFIC COAST BRANCH OF PALEONTOLOGICAL SOCIETY

CENOZOIC MARINE CLIMATES OF THE PACIFIC COAST

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The available data indicate that, within the range of normal marine temperatures, stenothermal organisms are more critically limited by minimum than by maximum temperatures. Using this fact together with associations of organisms, a study of the climates indicated by the marine fossil record of the Pacific Coast has been made. The available data indicate that during the Paleocene and Eocene, the 20-degree C. isotherm was north of 49° N. Lat., and that this isotherm gradually migrated southward to about 28° N. Lat. during the Tertiary, possibly with minor fluctations until the middle Pliocene; in the upper Pliocene it probably was near 30° N. Lat. During the Pleistocene this isotherm obviously shifted both northward and southward, at different intervals, but the stratigraphic data available do not permit correlation of these movements. The available data indicate that during the upper Cretaceous the 20-degree C. isotherm was at least as far north as during the Paleocene.

A reconnaissance examination of the data from other areas suggests that these climatic changes are not confined to the Pacific Coast but are world wide and are not related to any form of "Continental Drift" or other postulated rearrangements of the continental masses.

AGE OF THE *CORALLIOCHAMA* BEDS OF THE PACIFIC COAST

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When White described the peculiar Pacific Coast rudistid *Coralliochama* in 1885, he considered it as coming from beds of Middle Cretaceous age near Gualala, California, and from Todos Santos Bay, Lower California. Subsequent papers in which this fossil or the associated faunas are mentioned have usually cited a lower Upper Cretaceous age, for instance Anderson and Hanna in their 1935 paper on Lower California listed the "Punta Banda beds" (the *Coralliochama* bearing beds of Todos Santos Bay) as of Turonian age. Later Anderson (unpublished MS) concluded that the *Coralliochama* bearing beds were of Maestrichtian age, apparently largely on the basis of the occurrence of *Coralliochama* in the Cretaceous sections at Point Loma and La Jolla where the ammonites *Exiteloceras* and *Parapachydiscus* also occur.

Recently we have collected specimens of a nostocerid ammonite immediately below *Coralliochama*-bearing beds of the Gualala "Group", and a *Parapachydiscus catarinae* Anderson and Hanna from the Punta Banda *Coralliochama*-bearing beds. *P. catarinae* is similar to *P. ootacodensis* of the late Cretaceous of India, while the genus *Nostoceras* is known only from beds of Maestrichtian age. Thus the *Coralliochama*-bearing beds are probably of Maestrichtian age.

Some poorly preserved fossils from the Gualala "Group" near Stillwater Cove suggest the possibility of a lower Eocene or Paleocene age for part of the sequence.

HISTORY OF THE PACIFIC COAST BRANCH OF THE PALEONTOLOGICAL SOCIETY

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Agitation leading to the founding of the Paleontological Society began in 1907 when members of the former American Society of Vertebrate Paleontologists discussed the need for a broader association of all paleontologists. As a result of conversations with the Council of The Geological Society of America in 1908, preliminary plans for a paleontological society were formulated. The first annual meeting of the Paleontological Society was held at Harvard on December 29, 1909.

The Council of The Geological Society of America instructed J. C. Merriam, in October 1910, to

organize a "Pacific Coast Section of the Paleontological Society," and the Council suggested the name "Cordilleran Section of the Paleontological Society." According to transcribed records of the Le Conte Club, Doctor Merriam suggested at a meeting of that organization in December 1910 (more likely 1909) that persons interested in west coast paleontology should form an organization to further their interests. The suggestion was approved forthwith and the name "West Coast Palaeontological Society" was adopted. J. P. Smith was elected president of a temporary executive council.

The first annual meeting was held at the University of California at Berkeley on March 26, 1910. Ralph Arnold and J. R. Pemberton presented the society's first paper, entitled *Stratigraphy of the Ventura quadrangle.*

Almost as soon as the organization was firmly launched, the Paleontological Society invited the West Coast Paleontological Society to become affiliated with it. At the second annual meeting the members voted to make the affiliation, but the union was not completed for over a year, there being dissension as to whether the name should be the one suggested by the Council of The Geological Society of America or a name of the local members' own choosing. Apparently the opinion of the western paleontologists prevailed, for the fourth annual meeting in 1913 was the first held under the present name.

Meetings have been held annually except in 1918, 1943–1945. In this, the fortieth year of the society, the thirty-seventh annual meeting is scheduled. A compilation of historical material will be presented in the published report.

FORAMINIFERA OF THE TYPE MEGANOS FORMATION (EOCENE) OF CENTRAL CALIFORNIA

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The Meganos formation at its type area northeast to east of Mt. Diablo, California, yielded 201 species of Foraminifera of which 31 are restricted to the lower shales (Meganos C), 34 occur in the upper shale (Meganos E), and 136 range through both units. Twenty-four families and 82 genera are represented in the assemblage; of these, 21 families and 63 genera are common to both shale divisions, one family (Astrorhizidae) and 10 genera are restricted to Meganos C, and two families (Discocyclinidae and Camerinidae) and 9 genera are confined to Meganos E.

The four families Lagenidae, Buliminidae, Rotaliidae, and Anomalinidae comprise nearly two-thirds of the species. Ecologic distribution of living representatives of these families indicates that the sediments were probably deposited off a tropical or subtropical coast along the Continental Shelf in cool waters of medium depth.

This Meganos assemblage has many species in common with other Lower Tertiary formations of the State. Its greatest affinity is with the type Lodo (Paleocene and Eocene). Approximately 50 per cent of the 161 Lodo species occur in the Meganos. It includes also species similar to the Gulf Coast Claiborne and Wilcox, especially the latter. Correlation of Meganos C with the Wilcox (Lower Eocene) is suggested by its microfauna and stratigraphic position—namely, by the fact that it is overlain by a sandstone (Meganos D) with a megafauna of Wilcox age. Meganos E, above this sandstone, appears to be, in part, of Claiborne (Middle Eocene) age on the basis of its microfauna and a small collection of Middle Eocene megafossils from the Kellogg Creek area northwest of Byron.

REVIEW OF THE STRATIGRAPHY OF THE JOHN DAY FORMATION IN OREGON

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Since 1902 the John Day formation has been considered divisible into three parts: lower reddish trachytic tuffs, middle blue-green and upper buff andesitic tuffs. Early studies indicated that a rhyolite flow separates the middle and upper beds.

Plant remains from the lower beds have been determined as Upper Oligocene in character, and mammal remains in the middle and upper divisions as Lower Miocene. These latter remains were considered sufficiently different to confirm the results of lithologic studies.

Recent studies at Oregon State College indicate that the rhyolite is a welded tuff, ignimbrite, and this grades into the andesitic tuff of the upper division. Since the characteristics for the middle

and upper beds are the same, separated only by a local extrusive variant, it seems evident that any division is artificial.

Matrix colors on mammal specimens have been used as stratigraphic indicators, which is now untenable. The presence of *Diceratherium annectens* (Marsh) in upper beds makes the term "Diceratherium beds" for the middle division unusable. "*Promerycochoerus* has been identified from the middle division, and the term "Promerycochoerus beds" is inept for the upper beds.

Most of the mammalian specimens are of little or no value in correlating these beds since most of the materials are not accompanied by accurate stratigraphic data. New collections with adequate information may show some faunal differences, but for the present it seems best to consider the fossils from the andesites as representing one faunal unit.

NEW MARINE FAUNA FROM COOS BAY, OREGON

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The channel of Coos Bay, Oregon, was dredged to −31 feet mean lower low water during the spring of 1949. Dredgings from mile 2.0 to mile 4.5 were placed in two disposal areas beside the channel.

Some of the material dredged from the bay contains an abundant marine invertebrate fauna distinct from any exposed in the cliff sections along the beach or in outcrops farther inland. Possibly three distinct faunal assemblages are represented in this material.

The maximum length of pipe line used during the dredging was 2770 feet including pontoon and shore line, but the usual length was less than 2000 feet. Material in disposal areas was removed from a point in the channel within this radius. The approximate position in the channel of the material dredged may be determined with a moderate degree of accuracy.

A Pliocene Empire fauna occurs in the material dredged from mile 2.0 to mile 3.5 at the southwest end of the dredging. The material dredged from mile 3.5 to mile 4.0 contains a faunal assemblage that has not been previously reported in Oregon. The fauna resembles certain aspects of the Astoria fauna but includes some lower Miocene forms. Of particular note is the abundance of *Dosinia* cf. *merriami* Clark which has not been previously reported this far north. The material from mile 4.0 to mile 4.5 contains a microfauna correlated by R. E. Stewart with the upper Bastendorf formation.

STUDIES ON FOSSIL SILICOFLAGELLATES

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Recent studies of two faunules from the Kellogg and Sidney shales of upper Eocene age near Mount Diablo, California, have yielded new data about the paleobiology of silicoflagellates. Two of the more important contributions are: that the multitude of complex varieties of skeletal forms in the material studied can be reduced to 11 plans of growth; and that 50 per cent of the previously described species have been reported in Europe, South America, Asia, New Zealand, and the Barbados Islands.

The two assemblages of silicoflagellates studied are the largest thus far recorded from North America. Preliminary studies of more than 4200 specimens have resulted in a more refined concept of a species than that used in most literature on silicoflagellates. Forty-five species, including 2 new genera, 21 new species, and 2 new varieties have been recognized.

Modifications and evaluations of present-day techniques for the separation of specimens from matrix, and the preparation of individual mounts and strewn slides are discussed. Ecology, geographic distribution, and observable parallelisms of the skeleton with other organisms are presented.

PRELIMINARY PALEONTOLOGIC REPORT ON THE PALEOZOIC OF NORTHEASTERN WASHINGTON

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The Paleozoic rocks of Stevens County in northeastern Washington have yielded sufficient fossils to indicate that most of the periods of the Paleozoic era are represented in the county. Although

well-preserved specimens have been collected from relatively few localities strata of the Cambrian, Ordovician, Mississippian, and Permian systems are known to be present. There is less definite evidence for the presence of Devonian and Pennsylvanian strata, and nothing to date indicates that Silurian rocks are included in the section.

Fossils upon which these stratigraphic assignments are based include sponges, trilobites, graptolites, ostracodes, brachiopods, and fusulinids. The faunas now known show affinities to those of the Rocky Mountain Paleozoic sections as well as to those of Asiatic origin.

Methods attempted in extracting microfossils from the limestones are summarized, and those which were most successful are recommended to others who may be interested.

TERTIARY GEOSYNCLINE IN WESTERN ECUADOR AND COLOMBIA

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This article covers: (1) A description of the Bolivar geosyncline in its physical and geological aspects; (2) A stratigraphic table to show unconformities and formations in a brief form; (3) Historical geology; (4) Barriers to migration and intermingling of flora and fauna.

LOWER CAMBRIAN FOSSILS FROM NEAR ADDY, WASHINGTON

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A fossil collection, including the olenellid trilobite *Nevadia*, was made from the Addy quartzite near Addy, Stevens County, Washington. The Addy quartzite is considered equivalent in age to the Gypsy quartzite of the Metaline Falls area and to the Hamill quartzite of southeastern British Columbia. The quartzite underlies the Old Dominion limestone, which contains Lower Cambrian Pleospongea and the trilobite *Wanneria*, and probably represents a horizon very close to the base of the Lower Cambrian.

TERTIARY FORAMINIFERA FROM THE WILLAPA RIVER VALLEY OF SOUTHWEST WASHINGTON

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Tilted Tertiary strata with a stratigraphic thickness of well over 5000 feet are exposed along a 7-mile portion of the Willapa River Valley in the Menlo-Holcomb area of southwest Washington. These beds are for the most part sandy siltstones and represent an essentially continuous section of a substantial portion of the Pacific Northwest marine Tertiary. Of the numerous Foraminifera contained, 81 species belonging in 39 genera of 16 families have been studied with respect to environment of deposition and stratigraphic significance. These fossils seem to indicate a rather uniform marine environment at an off-shore shallow-to-intermediate depth. The fauna further suggests slightly warmer conditions than those now existing in bays of the Pacific Northwest. Foraminiferal evidence appears to indicate the presence of at least partial equivalents of the Cowlitz, Keasy, Lincoln, Blakely, and Astoria formations. Probably, therefore, the fossiliferous strata under consideration range in age from upper Eocene to lower Miocene.

PRELIMINARY REPORT OF A NEW VERTEBRATE LOCALITY NEAR PENDLETON, OREGON

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A new vertebrate locality has been discovered near Pendleton, Oregon, at McKay Reservoir. Action of the reservoir waters has revealed a varied fauna from the tuffaceous sandstone. Forms represented include: *Teleoceras*, *Merychippus*, *Prosthenops*, *Eucastor*, and other rodents, a camel, oredon, several carnivores, a mustilid, and birds.

The fauna, as tentatively identified, suggests a late Miocene or early Pliocene age. Material from the site with its large variety of forms should help clarify stratigraphic correlations of North-central Oregon and South-central Washington. Further work is being carried out by the University of Oregon Geology Department and Museum of Natural History, under a faculty research grant.

NEW EVIDENCE CONCERNING THE CHRONOLOGIC AND GEOGRAPHIC RANGE OF THE LONG-HORNED BISON OF NORTH AMERICA

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It is now generally agreed that *Bison* originated in Asia and dispersed to North America via the Bering region. It has been proposed that one of the first arrivals in southern North America was *Bison latifrons* (Harlan), the long-horned type. This *B. latifrons* population is said to have been spread over most of the United States in the middle Pleistocene (Kansan). The long-horned bison may have survived in Florida until late Pleistocene but presumably became extinct elsewhere by at least the time of Wisconsin glaciation.

B. latifrons horn cores have recently been discovered embedded in a surface soil in California. Cavities within these bones are also filled with soil. This discovery appears to be the most recent occurrence, geologically, of *Bison* in central California. Shorter-horned bison have been recovered from the later Pleistocene deposits of California, although these have never been found in association with *B. latifrons*. Recent *Bison* has not ranged into California.

Apparently several species of *Bison*, including *B. latifrons*, dispersed into this area sometime in the latter half of the epoch and survived until near Recent time. It is suggested that perhaps the California species were protected from the competition of more advanced types by a barrier of glacier-covered mountain ranges during the Tioga (= Wisconsin) interval.

NEW LOCALITY OF *DESMOSTYLUS HESPERUS* MARSH, FROM THE ASTORIA MIOCENE

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A fragmental skull with teeth has been recently collected from the Astoria Miocene at Astoria, Oregon. The two former specimens of *Desmostylus hesperus* from Oregon were collected from the Astoria Miocene near Yaquina Bay. One was a nearly complete skull, the only one from North America; the other was a set of molar teeth. A number of teeth and several fragmental mandibles have been collected from the Briones and Temblor Miocene of California.

All the columns of the teeth of the new specimen from Astoria are pointed. A thin section of one of these shows the enamel cones continue without interruption to the summit of the tooth column leaving no reason to believe as stated by VanderHoof (1937) that such a condition is abnormal. It would seem, then, that the craters on the summit of the teeth studied by VanderHoof were due to wear as earlier suggested by Marsh.

LATE CENOZOIC AVENUES OF DISPERSAL FOR TERRESTRIAL ANIMALS BETWEEN NORTH AMERICA AND SOUTH AMERICA

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Throughout most of the Cenozoic the dispersal of terrestrial vertebrates between North America and South America was blocked by water barriers. There were a few chance dispersions in early (Clarendonian) and middle (Hemphillian) Pliocene times, but with the initiation of epeirogenic disturbances in the late (Blancan) Pliocene a land route was established, and many mammals spread both ways across the isthmus. This pathway is blocked again today by a formidable barrier in a dense rain-forest that stretches across part of Panama and northwest Colombia. The discovery of mammoth and bison (post-Blancan in North America) remains in Central America and their absence in South America indicates that the rain-forest developed before these animals reached the southernmost latitudes of their distribution in Pleistocene times.

It is concluded that two orogenies, at least, in the Panamanian and northern Andes regions effected these barriers. The first uplift eliminated the earlier water barriers and probably was responsible, at least in part, for a six-months' dry and a six-months' rainy season along the Pacific slope in the Panamanian-Choco region. Furthermore, it is hypothesized that part of the Gulf of Panama and a strip of the Colombian continental shelf was above sea level at that time. After the second uplift, particularly in the northern Andes, warm moisture-laden air drawn toward the low-pressure area

east of the Andes condensed and precipitated over the coastal area and western mountain fronts. This has given part of Panama and northwest Colombia a perpetual rainy season and a rain-forest barrier that blocked the passageway for most of the later Pleistocene and Recent mammals.

MISSISSIPPIAN CEPHALOPODS FROM WESTERN UTAH

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An extensive collection of cephalopods has been secured from shale beds in the Confusion Range of western Utah. These specimens include representatives of *Mooreoceras*, *Pseudorthoceras*, *Bactrites*, *Cravenoceras? Goniatites?*, *Lyrogoniatites*, *Dimorphoceras*, *Epicanites*, and possibly one or two other forms. *Lyrogoniatites* is the most common generic element, but certain nautiloids are also relatively abundant. *Epicanites* and *Dimorphoceras* are rare. In generic composition this assemblage is very close to those known from the White Pine shale of Nevada, the Caney shale of Oklahoma, and the Barnett formation of central Texas.

PRELIMINARY REPORT ON TWO CAPACITY TRANSDUCER SEISMOGRAPHS

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An experimental model seismometer using a capacity transducer has been put into operation. The pendulum is of the torsion type with an inertia-reacter of approximately 1 kg. mass. Damping is provided by a coil moving in a magnetic field with leads attached to the upper and lower torsion ribbons which are insulated from each other. Damping can be adjusted with an external resistance, and any change in period brought about by reaction of the magnetic field on the coil is accounted for. The variable capacity consists of a fixed plate separated about 1 mm. from a movable plate attached to a light boom on the cylinder. The mechanical magnification is approximately 5. The seismometer capacitor serves to couple the grid and plate circuits of a tuned-grid tuned-plate oscillator. The amplitude of oscillation varies very nearly linearly with the capacity variation of the pendulum condenser. A voltage output is derived from the oscillator grid leak and is coupled to a one-stage seismic frequency amplifier by means of a resistance capacity network. The output of the amplifier is also obtained through a resistance capacity network. The time constants of the coupling circuits respond to seismic waves up to 60 seconds period. A short-period galvanometer 0.1 to 0.3 second period is used for recording.

EARTHQUAKES AND ROCK CREEP

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The accumulated strain-rebound curve of all world earthquakes of magnitudes 8.0 to 8.6 which have occurred since 1904 exhibits a saw-tooth shape with very nearly linear segments. The serrations decrease regularly with time in amplitude as well as in period. If a proposed interpretaton is correct, the curve indicates the following conclusions: (1) World earthquakes in this magnitude range are not independent events. They are related in some form of world-wide stress system. (2) From 1908 to 1950 the total secular strain accumulated at a remarkably constant rate. (3) This strain was released in five active periods of decreasing lengths separated by quiescent intervals of very slight or no activity. (4) During the active periods the strain release proceeded at approximately twice the rate of the secular strain accumulation.

A study of the Mount Pelee sequence of volcanic eruptions of 1902 as reported by Jaggar indicates that this sequence may have been produced by compressional elastic creep of the volcano rock in much the same manner as the aftershock sequences of earthquakes are produced. We may assume that the rock was in a state of compression preceding the initial eruption and that the first outbreak was produced by elastic release of the rock. The vent then became sealed by a liquid column or otherwise, and the volcano remained quiescent until the elastic afterworking of the rock raised the pressure sufficiently to break the seal and thus generate the second outbreak. The process was repeated seven times more at lengthening intervals in accordance with the creep characteristics of the rock.

GRAPHICAL METHOD FOR SOLVING VIBRATION PROBLEMS OF A SINGLE DEGREE OF FREEDOM

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The graphical method reviewed here was described by J. Lamoen and is a specialization of the phase plane representation commonly used for systems of a single degree of freedom. The present paper shows how the graphical method may be extended to treat systems for which the "deflection vs. restoring force" curve may have regions in which the slope is negative, and a discussion of the free vibration of such a system is included. The method is of much greater generality, however, and may possibly be used to find the approximate response of a seismograph pendulum to a prescribed

ground motion where the support of the pendulum at the same time is caused to deviate from its originally vertical position. Reference is also made to convenient methods for handling damping forces of various types.

SLOW SURFACE WAVES

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The Fresno seismographic station, located on deep valley alluvium, records several groups of very slow surface waves. They are of both Love and Rayleigh types and often show sharp cutoffs. They are interpreted as associated with minimum group velocities of alluvium-basement coupled waves. Their speeds are about half a kilometer per second.

FALSE S

Perry Byerly and Jack F. Evernden
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There is accumulating evidence that False S, as observed for years from some earthquakes off the coast of northern California, may come only from shocks centering along the steep submarine escarpment off Cape Mendocino. Shepard has suggested that this is a fault scarp.

VIBRATION AND TILT STUDIES ON SATHER TOWER, UNIVERSITY OF CALIFORNIA, BERKELEY, CALIFORNIA

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Part 1 describes vibration observations made in Sather Tower during 1948 and 1949 by the Seismological Field Survey. Results given are the first three modes of translatory vibration in two directions, one mode of translatory vibration peculiar to the upper portion of the structure, and one mode of torsional vibration.

Part 2 describes the joint program developed by the Seismological Field Survey and the University of California Department of Civil Engineering for determining the relation between the sun's heat and movement of Sather Tower. Measurements of deflections and temperature changes are presented, and the results are discussed from the standpoint of tilt measurement and instrumental performance.

VIBRATIONS OF TRANSVERSE WAVES IN SOUTHERN CALIFORNIAN EARTHQUAKES AND CORRESPONDING FAULT MOVEMENTS

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The direction of first motion of transverse waves from numerous local earthquakes in Southern California is investigated. The direct wave, which presumably encounters no discontinuities between the source and receiving station, appears to be approximately polarized. The *SH* components of these waves have strikingly consistent directions of first motion within the area, while the *SV* components appear to be more contradictory. The first motions of the *SH* and *SV* waves are found to have components in the same direction as the fault block displacements. Interpretation of the data suggests that two fault types are prevalent in the area. The predominant one is of the San Andreas type, a northwesterly trending transcurrent fault. The other may be of a thrust fault nature. The two fault types seem to be localized, each appearing separately within particular regions. Possible stress distributions resulting in these fault patterns are discussed.

LONGITUDINAL WAVES THROUGH THE EARTH'S CORE

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The amplitudes, periods, and travel times of P' and P'' have been investigated. Results indicate that the epicentral distance of the main P' focal point varies with period: for longer period waves the focal point occurs near 143 degrees; for shorter period waves near 147 degrees. The position of the end of the reversed segment of the travel-time curve for waves through the outer core is believed to be near 159 degrees.

Travel times show that the P' and P'' waves are recorded as three groups separated by intervals of 10 and 20 seconds. Each group has its corresponding focal point. This indicates that core waves suffer dispersion.

From 110 degrees to greater distances the period of the main P'' phase increases with increasing distance; near 110 degrees short-period waves carry the largest fraction of the energy. This relation may be interpreted as a consequence of rapid velocity increase with increasing depth at the transition to the inner core.

Further investigations to extend this study to determinations of core velocities and structure are discussed.

ENERGY RATIOS OF WAVES REFLECTED AND REFRACTED AT A ROCK-WATER BOUNDARY

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Using the Knott-Zoeppritz equations, the general behavior, zero points, and extreme points of the energy ratio that go into the waves reflected and refracted upon the incidence of a wave at either side of a rock-water boundary at the bottom of the ocean are computed as a function of the angle of incidence for a possible range of values of the parameters involved, namely, Poisson's ratio, the ratio of the longitudinal wave velocities in two media, and the density ratio.

From the computed results it is found that:

1. Poisson's ratio of the solid medium is a dominating factor in the general behavior, zero points, and extreme points of the reflected and refracted waves that travel in the solid.
2. Changes in the ratio of the two longitudinal velocity ratio produce pronounced results in the refracted wave energy only.
3. The effect of changing the density ratio is very slight.
4. Peculiar behaviors occur just before and right after the critical angle of incidences.
5. At a critical angle of incidence, all the incident energy goes into the reflected wave of the same kind as the incident wave.
6. Most of the incident energy is reflected either as P or as S wave depending upon the angle of incidence.

AMPLITUDES OF PcP, PcS, ScP, AND ScS IN DEEP-FOCUS EARTHQUAKES

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A systematic study is being made of the displacement ratios of the core reflections to the direct body waves, using intermediate and deep-focus earthquake seismograms recorded at the Seismological Laboratory in Pasadena. Theoretical values of the horizontal and vertical ground displacements have been computed for the direct P and S as well as PcP, PcS, ScS, ScP, as a function of the epicentral distances for three different focal depths, namely, $h = 100, 400, 700$ km. The results obtained so far indicate that the observed ratios of the horizontal displacements of the waves that are reflected as P waves at the core boundary to that of the incident wave (*i.e.*, PcP/P, and ScP/SV) are 5 to 10 times larger than the theoretical ratios. The observed ratios of the vertical displacements are only 2 or 3 times larger than the theoretical ones. For the waves that are reflected as S wave at the core

boundary, the observed ratios (*i.e.*, *ScS/S*, *PcS/P*) of the horizontal displacements are in fairly good agreement with the theoretical ratios, but the observed vertical ratios for same waves are considerably larger than the theoretical ratios. The result for *ScSS/V* is less anomalous than that for *PcS/P*.

No appreciable effect of the depth of focus in the observed discrepancies is indicated by the results.

REVISED TRAVEL TIME CURVES FOR SOUTHERN CALIFORNIA

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Data from blasts in southern California indicate that the velocity of longitudinal waves increases in the uppermost 10 kilometers from about 5.7 km/sec to about 6.5. This disagrees with the values calculated from earthquake records on the assumption that $\bar{P}$ and $\bar{S}$ at distances greater than about 80 kilometers are direct body waves. It was therefore suggested by the author (Science, vol. 111, p. 29, 1950) that this assumption is incorrect. New calculations are based on records of 50 earthquakes (Bull. Seismol. Soc. Am., vol. 34, p. 13–32, 1944). *S-P* intervals plotted as a function of distance give 0.115 for the difference of the reciprocals of the "average" two velocities and an average focal depth of 16 kilometers. A ratio of 1.73 of the two velocities is found from travel-time ratios of *P* and *S* over given distance intervals. These findings combined give 6.35 and 3.67 km/sec respectively for the two "average" velocities. Origin times calculated on this basis are in general slightly over 1 second later than had been found previously. Other phases are reinterpreted in the light of the new findings. The amplitudes of the direct *P* waves decrease more rapidly with distance than when calculated for constant velocity, thus indicating a decrease of velocity with depth near the focus. *Pn* arrives slightly less than 2 seconds later in blasts than in earthquakes, indicating a depth of focus slightly less than 20 kilometers. Other findings in general agree with the views expressed recently by the author (Science).

DIRECTION OF FAULTING IN CERTAIN EARTHQUAKES OF THE NORTH PACIFIC

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Byerly's method, whereby a consideration of the distribution of initial compressions and rarefactions leads to an indication of fault direction, is extended to a general case. Geometrical considerations lead to certain simple criteria which must be satisfied in applying the method. These criteria are actually helpful rather than restrictive.

The extended theory is applied to the Aleutian earthquake of April 1, 1946, to the Alaskan earthquake of October 16, 1947, to the British Columbia earthquake of June 23, 1946, and to the Queen Charlotte Island earthquake of August 22, 1949. The results in each case are discussed in the light of other data available and are shown to be reasonable.

SEISMIC WAVES AT SHORT DISTANCES; PROGRESS REPORT

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Recently installed temporary seismological stations in southern California supply data for redetermination of wave velocities. Results for seven shocks are in course of publication. The best value for the mean velocity of *P* at short distances at this writing is 6.337 km/sec. Investigation has been extended to four small quarry blasts, to later earthquakes, and to the Desert Hot Springs shocks of December, 1948, which were recorded at temporary stations at short distances.

To improve the value taken for the mean velocity, *D* was calculated from the values of Δ given in Table 2, assuming $h = 16$ km; residuals in time of first motion were computed for $t = 0.158\ D$, reducing the observed times at *MW*, *Cr*, and *Pr* by 0.1 second. Shocks 1 to 7 showed individual systematic deviations for all stations. The assumed origin times were altered by the means of these

deviations, which for the seven shocks were in order -0.37, $+0.36$, $+0.11$, $+0.37$, $+0.32$, -0.29, -0.26 (seconds). The plotted residuals then fit a straight line with wholly negligible deviations. The best fit is for $t = 0.1578\ D$, which corresponds to $v = 6.337$ km/sec.

FAULTS AND EARTHQUAKE POSSIBILITIES IN OREGON

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The recent severe earthquake in the Seattle area was felt in many parts of Oregon, especially in the northwestern portion. This has prompted the Oregon section of the American Society of Civil Engineers to recommend the adoption of a building code to meet the earthquake hazards in this State.

Oregon has experienced an earthquake in some part of the State each year since 1846. The severest yet recorded, intensity VIII, was on July 15, 1936, in the vicinity of Milton-Freewater in the extreme northeastern corner of the State. The last one of which we have any record was in August of last year.

In view of the many large multi-purpose dams being constructed in many parts of the State at present it seems pertinent to review the earthquake situation.

Some of the major tectonic lines, especially faults, are discussed in the paper and possible theories to explain the relatively moderate activity along most of them.

Recommendations for future seismological investigations are made.

S WAVES AS DIAGNOSTIC OF FAULT MOTION

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A study of the records of *SH* at 11 seismographic stations for the (Mina) Nevada earthquake of 1932 leads to a fault direction consistent with the geology of the region and a fault motion consistent with that recognized in California. For this shock no consistent relationship appears to hold for the direction of first motion of *P*.

ABSTRACTS OF PAPERS SUBMITTED TO THE MEETING IN GOLDEN, COLORADO APRIL 14–15, 1950

ROCKY MOUNTAIN SECTION OF THE GEOLOGICAL SOCIETY OF AMERICA

FIELD PERMEABILITY TESTS USED BY THE BUREAU OF RECLAMATION

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In Bureau of Reclamation work, engineering considerations frequently require determinations of relative permeabilities of different beds or changes in permeability with depth. Laboratory tests of field specimens are frequently unsatisfactory due to the disturbed condition of samples, cost of testing a representative group of samples, and other factors.

Thiem-Forchheimer tests are used extensively in saturated materials under certain conditions, utilizing Theis', Taylor and Raineville's, and Thiem-Forchheimer's equations for computing permeabilities. These tests permit determination of average permeabilities only.

A number of "pump-in" tests have been adapted for use in Bureau work which permit determinations of relative permeabilities between different beds and at different depths under saturated or unsaturated conditions. Similar tests used by the Bureau have been subject to considerable error. Experimental field and laboratory work has resulted in improvements in techniques and equipment, and consequent elimination of some of the major sources of error. Present results are theoretically accurate within plus 15 per cent. Although the actual error is greater in some instances, the results are still adequate for some engineering applications. Improvement of techniques and equipment is continuing.

"Pump-in" tests require measurement of the hydrostatic head effective on the test section, physical dimensions of the section, and the uniform inflow of water required to maintain a constant head on the section. The thickness of unsaturated material above the water table or the thickness of the saturated material below the water table must be determined.

SIGNIFICANCE OF THE ARCUATE STRUCTURES OF THE NORTHEAST FLANK OF THE LARAMIE RANGE

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The arcuate folds and associated faults on the northeast flank of the Laramie Range were formed during the Laramide revolution. Axial planes of the folds and the planes of the faults dip northeast. This is in opposition to the general structural pattern of the Laramie and Front ranges.

A "push-block" theory of genesis is proposed.

A positive relationship between Precambrian and post-Cambrian structures seems probable.

PROBLEMS OF THE STRUCTURE AND STRATIGRAPHY OF THE UPPER SWEETWATER VALLEY, WEST-CENTRAL WYOMING

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Approximately 1000 square miles along the upper Sweetwater Valley at the south end of the Wind River Range in west-central Wyoming has been mapped during the past 2 years. The structural and erosional history of the intricately folded and faulted areas is so complex that, in order to determine the sequence of events, it has been necessary to study in detail the Precambrian and Tertiary rocks as well as the strongly deformed Paleozoic and Mesozoic strata.

Precambrian structure has influenced Laramide deformation. A large mass of metasediments surrounded by granitic rocks transects the southern Wind River Range and established a zone of weakness along which the Laramide structures developed.

Laramide deformation resulted in two principal features: the large thrust fault on which the Wind River Range has moved westward; and the thrust fault on which the remnant of the overriding block exposed at Crooks Mountain moved southward. All other Laramide structures are related to these major features.

Cenozoic sediments cover much of the area and are complexly intergrading facies of more extensive deposits in the Wind River Basin to the north and the Great Divide Basin to the south.

A conspicuous feature of Lower Eocene in front of both major thrusts are deposits of large boulders derived from the advancing thrust sheets. Cenozoic sedimentation was intimately associated with both tectonic adjustment, which was operative from late Cretaceous to at least the close of Miocene time, and with extensive vulcanism in adjacent areas.

These late Tertiary and possibly Quaternary movements have interrupted all erosional and depositional cycles established during earlier quiescent intervals.

STRUCTURE IN THE PRECAMBRIAN WEST OF DENVER

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The strong primary northwest-southeast trend of folds, faults, and intrusions in the Precambrian west of the foothills between Clear Creek and Turkey Creek, Denver Mountain Parks area, is interrupted, locally, by minor north-south and east-west structures.

Small, broad, open, north-south folds, nosing out to the south, cross Mount Vernon Canyon. Normal faults, with downthrow to the east, offset the formations. Thrusts from the east have sliced the Precambrian rocks close to the foothills. Low-angle underthrusts occur. Maps, cross sections, diagrams, and colored views will be presented to show the features and their meanings.

GEOLOGY OF THE EASTERN PART OF FLAT TOP ANTICLINE, ALBANY AND CARBON COUNTIES, WYOMING

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The geology of an 85-square-mile area in the north-central part of the Laramie Basin, northeast of Medicine Bow, Carbon County, Wyoming, is presented. The report includes detailed stratigraphic sections and a geologic map with accompanying structural sections on a scale of 1:31,500. Sedimentary rocks from Pennsylvanian to Cretaceous age occur in the mapped area. The major structure is the northeastward-trending, asymmetrical, Flat Top anticline. The northwest and steeper flank of the anticline is faulted by the southward-dipping Flat Top thrust. The folding which produced the anticline probably arose as the result of upward, basement-block movement caused by northeast-southwest compressional forces in late Cretaceous time. Interpretations of local geologic features and their relations to the regional geology are briefly discussed.

STRUCTURAL HISTORY OF THE CANYON RANGE, WEST-CENTRAL UTAH

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Stages in the development of the Canyon Range have been determined from structural and stratigraphic relationships of the following sedimentary units: Precambrian (?) quartzite, shale, and slate; Tintic quartzite (Lower Cambrian); Ophir shale (Middle Cambrian); undifferentiated limestones and dolomites (Upper Cambrian and Ordovician); Indianola group (Upper Cretaceous); North Horn and Flagstaff (late Cretaceous and Paleocene); Oligocene (?) conglomerates; and Pleistocene and Recent alluvium. The following series of events is indicated: (1) Uplift accompanied by folding and large-scale thrusting, beginning in late Jurassic (?) time and culminating in early Cretaceous time; (2) Deep erosion; (3) Deposition of thick series of coarse clastic continental sediments (Indianola group); (4) Folding and high-angle thrust faulting in post-Indianola time, previous thrust plane folded and Precambrian rocks thrust over Cretaceous rocks; (5) Deposition of continental sediments in marginal basins (North Horn and Flagstaff); (6) Moderate folding in post-Flagstaff time; (7) Development of essentially the present drainage systems; (8) Deposition of Oligocene (?) conglomerates on piedmont slopes and in canyons and valleys within range; (9) Tilting of Oligocene (?) conglomerates; (10) Basin and Range faulting beginning in Miocene (?) time and continuing to Recent; (11) Alluviation of piedmonts and deposition of Bonneville sediments followed by post-Bonneville dissection.

GEOLOGIC STRUCTURES IN WESTERN NEBRASKA AND ADJOINING AREAS

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Agate, Nebr.

The Cretaceous to Pleistocene history of the areas, and the genesis of Tertiary structures are discussed. Tertiary sedimentation indicates that, although the Julesburg basin was emergent and rising while the Powder River basin was subsiding after Cretaceous times, both these areas, in fact the whole Rocky Mountain Province area, were much nearer sea level at the opening of the Oligocene than now.

The entire Rocky Mountain region was massively elevated during the Miocene to Pliocene activities of the Rocky revolution, with attendant local effects of folding and faulting, but with generally less noticeable diastrophic and orogenic effects than in the Laramide revolution, although this Miocene disturbance was world-wide and profound in its effects.

Tertiary depositional stages date diastrophic activities here. A study of the master streams and their geologic history further confirms the correlation of these activities.

With proper evaluation of evidence a great deal can be told about the structure in many of the Cretaceous, and older, potential oil and gas traps still to be drilled and tested in this region.

HYDROTHERMAL ALTERATION EFFECTS IN THE LEADVILLE LIMESTONE AND THEIR RELATION TO METALLIZATION

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The Leadville limestone has been a favorable horizon for ore deposition in a number of central Colorado mining districts. In the Alma, Leadville, and Gilman districts, this formation is ore-bearing and is partially or completely dolomitized. The relations of hydrothermal dolomitization and other widespread hydrothermal effects to metallization are considered through the variations in porosity, $CaCO_3/MgCO_3$ ratio, and the percentage of impurities. The possible use of one or more of these properties as guides to ore is suggested.

Parallel studies were made of an apparently nonhydrothermal, though dolomitic, facies of the Leadville limestone and of a dolomite which underlies and is locally less favorable than the Leadville formation.

GEOLOGIC PROBLEMS OF A PORTION OF THE MISSOURI RIVER BASIN PROJECT

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Many problems confront geologists and engineers in locating stable sites for the many engineering structures to be built within the confines of this project.

Poorly cemented but extremely consolidated materials of the Fox Hills, Lance, Fort Union, and Wind River formations constitute the bedrock or foundation rock for the engineering structures at many places. Loess, glacial till, and the weathering product of the above-mentioned formations are foundation materials for structures at other places where it is not feasible to excavate to sufficient depth to expose materials classified geologically as rock.

Large reservoirs for irrigation reserve and to handle maximum floods require large dams (usually of earth) and appurtenant structures. Due to many undesirable characteristics of the foundation material, such as friability, lenticularity, instability of steep slopes when saturated, softness, and erodability, it has been necessary for the engineer to consider rather drastic departures from standard designs.

Suitable construction materials, especially sand, gravel, riprap, and in some instances the earth materials for dams in these areas often are scarce or lacking, necessitating importation from distant sources or the design of an earth dam with unusual zoning of materials.

It has been necessary to do extensive and unusual surface and subsurface exploration in an effort to delineate fully the foundation condition for each major structure; some of the problems encountered have not yet been satisfactorily solved.

STRUCTURE AND GEOMORPHOLOGY OF SOUTHWESTERN MONTANA

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A fairly sharp rise on the west cast the Lower Cretaceous Kootenay eastward over the area, and a second rise resulted in the Dakota (?) and Colorado clastics. The Aspen formation is over 3000 feet thick in Beaverhead County south of Lima. No Montana sediments have been recognized west of the Madison Range.

A northeastward-trending arch of about the proportions of the Bighorn Range rose in latest Cretaceous or Paleocene time. Its southeast flank is in places overthrust and makes up the present Snowcrest and Greenhorn ranges. Its northwest flank, with gentle dips, constitutes the northern part of the Blacktail Mountains. A great alluvial apron formed immediately following the uplift, to be consolidated into the present Beaverhead and Sphinx conglomerates.

The region was then compressed by northeastward and southwestward acting forces, and a number of thrust sheets trending northwesterly almost obliterated the arch across which they trended. The thrust sheets on the southwest emerge from the Snake River lava plains and are a continuation of the folded and thrust geosynclinal sediments of western Wyoming and eastern Idaho. The thrust faults on the northeast emerge from the Yellowstone Park volcanics and affect the shelf facies, with the Precambrian much exposed and in thrust relation to the younger sediments. Thrusting on the southwest is known to have occurred in two places.

By late Eocene extensive intermontane valleys had been eroded to a large extent in the Precambrian rocks and with the onset of volcanism became successively the sites of deposition of at least five formations. Some crustal unrest produced unconformities between these units.

Block faulting started in latest Miocene time and has continued at intervals to the present. The block faults connect the troughs of northwestern Montana and British Columbia with those of eastern Idaho.

HIGH-LEVEL GRAVELS WEST OF GOLDEN, COLORADO, AND THEIR PHYSIOGRAPHIC SIGNIFICANCE

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Several previously unreported occurrences of high-level gravels in the Clear Creek drainage system between Golden and Idaho Springs, Colorado, are described, and the bearing of this supplemental information upon the rival interpretations of the physiographic history of the Front Range is considered.

STRUCTURAL CONTROL OF LIMESTONE ALTERATION IN THE MONARCH MINING DISTRICT, COLORADO

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A thick belt of lower Paleozoic limestones and dolomites in the Monarch Mining District, Chaffee County, Colorado, illustrates several sharp Laramide folds whose axes strike north-south and plunge north. In Taylor Gulch, the limb between two folds is complicated by smaller isoclinal folds denoting abnormally severe stresses. Deformation resulting from these stresses prepared the limestone section for selective hydrothermal alterations.

The sequence of Laramide events prior to emplacement of the Mt. Princeton batholith was isoclinal folding with attendant development of axial-plane cleavage, thrust faulting parallel to fold axes, and cross faulting perpendicular to fold axes, thus dividing the limestone into blocks. The bounding faults and cleavage zones served as channels or barriers to circulating emanations from the batholith. Limestone alterations, except for blanket recrystallization and silication close to the igneous contact, were fissure- and joint-controlled. Solutions showed marked selectivity for certain blocks and certain beds and horizons within blocks. Devonian and Mississippian beds show the greatest changes. Intensity of alteration decreases from the batholith contact toward Monarch Hill.

Blanket recrystallization is related to isoclinal folding. Dolomitization is believed earlier than

hydrothermal silication. Silication near the batholith, most of which is probably contact pyrometasomatic, produced garnet, epidote, diopside, and actinolite; farther away, tremolite, wollastonite, adularia, chlorite, and clay were formed. Silicification, pyritization, and sanding of the dolomite followed. Commonly, channels became clogged with early products, and later solutions were controlled by a different system of openings.

SAND POCKETS AND BRECCIA IN THE LEADVILLE LIMESTONE STAR BASIN AREA, COLORADO

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A zone of sand pockets occupying solution cavities overlies a band of mineralized brecciated limestone in the Leadville formation (Mississippian) at Star Basin on the western rim of Taylor Park, Colorado. The brecciated zone and the associated sand pockets have the same attitude as the enclosing Leadville limestone. The sand is poorly sorted, unconsolidated, cross-bedded; varies from fine- to medium-grained; and contains well-rounded pebbles of limestone. Surrounding the sand of each pocket is a band of clay about 1 inch thick, showing banded structure parallel to the walls. Heavy-mineral studies of the unconsolidated sand indicate that it may have been derived from a biotite gneiss. No closely associated sandstone beds from which the sand fillings could have been derived have been found in the sedimentary section at Star Basin.

The solution cavities were formed at or below the water table along one stratigraphic horizon in the Leadville limestone. The underlying breccia was probably derived from the partial collapse of the cavities prior to the infiltration of the sand. Tectonic movements later raised the solution cavities above the water table, and the cavities were then filled with the unconsolidated sand that was presumably derived from the erosion of an exposed Precambrian gneissic area.

PRISTINE MONADNOCKS

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Observations of the Rocky Mountains begun in 1909 led to the working concept that the large rounded mounts situated upon the inter-major stream and Continental divides in the Front Range are primordial monadnocks; that they were roughed out in Precambrian time as integral parts of the base-level surface developed upon the old Basement Complex; that they were shaped a little more before Morrison time, and possibly polished up during the Tertiary.

This concept is at variance with most published descriptions of the physiography of the range. A few authors briefly mention monadnocks. Most writers imply that the physiography is almost wholly the product of erosion since the Mesozoic era.

The physiography of the range consists of two cycles in juxtaposition: smooth old age and angular youth. The angular asymmetrical youth is unconformable with the rounded symmetrical. The hiatus between them amounts to many many millions of years.

Criteria for identifying pristine monadnocks are:(1) they must be composed of Basement Complex rocks; (2) they must be smooth, rounded mounts; (3) they must be generally mounts upon high divides; (4) they must have long slopes toward the Continental Divide with low col between them and the Divide; (5) where situated on the Divide they must have long smooth slopes both directions divideward.

Examples: St. Vrain, Meadow, Audubon, Bald. Partially destroyed now half domes or less: Evans, Longs, Ida, Arapahoe. All have persisted forever either uncovered or covered by sedimentary beds.

ENGINEERING GEOLOGIC INVESTIGATIONS—HUNGRY HORSE PROJECT, MONTANA

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The Hungry Horse Dam, now under construction on the south fork of the Flathead River, will rise 564 feet above the foundation excavation and will be the third highest dam in the world. The concrete arch structure will impound 3,500,000 acre-feet of water in a reservoir 30 miles long. The dam is founded on Siyeh limestone, a member of the Belt series. Exploration, by dimaond drilling,

tunneling, and surface mapping, proved the foundation to be excellent. Stripping has corroborated this conclusion.

The major geological problem at the project was the exploration of Abbott Gorge, a glacial debris-filled channel. Surface mapping seemed to indicate that the channel intersected the reservoir rim, bypassed the dam, and could serve as a path of leakage from the reservoir to the Flathead River. Exploration in the early stage of project investigation consisted of five holes drilled on a line across the channel. This work outlined a preglacial gorge 2500 feet wide, 300 or more feet deep, filled with glacial debris. Since appreciable leakage from the reservoir through the channel might seriously affect the feasibility of the project, it was necessary to prove either that the channel fill was impervious or that in some portion of the channel there existed a bedrock ridge higher than the reservoir flow line. Geophysical bedrock depth points secured with a refraction seismograph and spot checked by diamond drilling located such a ridge, and it was concluded that no leakage would occur through the channel.

EVIDENCE OF UPLIFT IN THE BIGHORN MOUNTAINS DURING UPPER CRETACEOUS TIME

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Local uplift in the Bighorn Mountains during Upper Cretaceous time is indicated by the deposition of chert pebbles and andesite porphyry pebbles and cobbles in the Frontier formation. The chert pebbles contain fossils of Mississippian (?) and Pennsylvanian age. Some andesite cobbles on the west flank of the mountains are 10 inches in diameter which precludes transportation from western Wyoming and Utah, the accepted source of Upper Cretaceous sediments. The source of the andesite porphyry, which has not been found, may have been a dike or sill removed by subsequent erosion.

LOESS AS A FOUNDATION MATERIAL

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Many of the proposed Bureau of Reclamation structures in Nebraska and Kansas will be founded on loessial materials. Laboratory studies and field observations on constructed projects have led to the conclusion that loess is a critical material with regard to consolidation, stability, and permeability. The Bureau of Reclamation's Petrographic and Earth Materials Laboratories have performed numerous tests to obtain definitive data on the nature of loess. These tests have disclosed that: (1) numerous vertical root holes are present, (2) a clay film surrounds each individual soil particle, (3) the loess will stand in a near-vertical bank when excavated, (4) vertical permeability is much greater than horizontal permeability, (5) saturating loess prior to loading softens the clay binder so that later loading will quickly cause consolidation, (6) undisturbed, unsaturated material will withstand considerable loads without excessive settlements, (7) serious settlements may occur if the undisturbed material is loaded and subsequently saturated by canal or reservoir water.

The major consideration in these tests has been to find a method of inducing consolidation at such a stage in construction that it will not seriously affect the completed structure. Proposed methods are: (1) saturating the foundation prior to treatment, (2) mud jacking under the footings of the structure after the water table in the loess has risen sufficiently to lubricate the individual loess particles.

Field tests supply data which will permit an analysis of whether special treatment will be required. These data can be interpreted to estimate the amount of settlement expected when the structure finally is built and the foundation soils become saturated by canal or reservoir water.

OÖLITIC IRON ORES OF NEW MEXICO*

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The Bliss sandstone (Upper Cambrian) of southern New Mexico contains beds of oölitic hematite up to 15 feet thick. These are exposed in outcrops up to several miles long in the Caballos, San

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Andres, Black, and Silver City ranges. The oölitic ores appear to be associated with a more calcareous, glauconitic, and hematitic facies of the Bliss sandstone. It is concluded that the iron content of the ore beds is almost entirely syngenetic and that deposition may have been mechanical as well as chemical. Much diagenetic rearrangement has taken place in the ores, and considerable recrystallization of hematite resulting in various stages of the obliteration of oöliths is of special interest.

ORIGIN OF SOME COLORADO PRECAMBRIAN GRANITES BY FUSION OF SEDIMENTS*

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During geologic work in the Mineral Belt of Colorado since 1930 the writer has had an opportunity to study parts of several bodies of Precambrian granites, including such well-known varieties as the Pikes Peak, Cripple Creek, and Silver Plume granites as well as several that are little known.

Microscopic study has revealed that the quartz, whether abundant or rare, is decidedly different in habit from that of normal granites and is the earliest mineral. The quartz occurs as rounded inclusions in the feldspars and in irregular clusters that consist of mosaics of quartz grains or of aggregates of sutured grains and in general resemble quartzite. Much of the quartz is decidedly more fractured than the feldspars. The feldspars, including plagioclase, microcline, microperthite, and orthoclase, are interstitial to the quartz and have formed along grain boundaries or along fractures in the quartz. They also form irregular lobes or tongues that cut across the quartz clusters, irrespective of grain boundaries, and in places occur as ramifying and branching stringers that form a boxwork surrounding quartz clusters. These relations, together with the rounded inclusions of quartz in the feldspars, show not only that the quartz is earlier than the feldspars, but also that it was partially replaced by them. Thus both the texture of the quartz and the paragenetic relations between the quartz and the feldspars suggest that the quartz is relict from a pre-existent rock, probably an impure sandstone.

The granites are essentially homogeneous in composition and texture over wide areas. They intrude the gneiss and schist of the Idaho Springs formation and show crosscutting relations with the country rock. The field relations and microscopic evidence imply that the granites crystallized from a magma formed by partial fusion of ancient sedimentary rocks.

ADDITIONAL COMMENTS ON THE STRATIGRAPHIC DISTRIBUTION OF *ORBULINA UNIVERSA* D'ORBIGNY

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In 1948 the writer suggested that points of lowest stratigraphic occurrence of *Orbulina universa* d'Orbigny in a continuously deposited, deep-water, open-sea, globigerine facies fall on or near a time horizon within Middle Tertiary sectons of present tropical and subtropical areas of the world. These "points" constitute the *Orbulina* surface. The Kassikan section of Central Sumatra is believed to fulfill all requirements for a qualified point. The lowest biostratigraphic occurrence of *Orbulina universa* has been established in Central Sumatra (base of middle Miocene), Southern Turkey (base of Lower Miocene), Algeria (base of lower Miocene), North-Central Venezuela (within middle Oligocene), Ecuador (base of upper Oligocene), Trinidad (base of upper Oligocene), and on the Pacific Coast (within upper Miocene). The terms Miocene and Oligocene as used here may not possess contemporaneous time values in widely separated areas. Therefore, if the *Orbulina* surface can be accurately established in low-latitude regions, drastic adjustments of many present age assignments expressed in European terminology will be necessary.

CONTRIBUTION TO THE GEOMORPHOLOGY OF THE RATON MESA AREA

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The component parts of the Raton Mesa area are readily separable into three well-defined geographic units: lava-capped mesas, dissected highlands, and lowland plains. The mesas owe their

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existence to the repeated extrusion and erosion of basaltic sheets at widely separated intervals. Attention is directed to the significance of local erosional and depositional land forms which are regarded as a key to the sequence of geologic events that have dominated the complex physiographic development of the region. The age of the high-level lavas protecting the remnant or remnants of a widespread graded surface is critical in this regard. The writer found no fossils in the sporadic deposits of sand, gravel, and water-worn cobbles underlying these lavas, but the discovery of weathered, vesicular basalt pebbles in the gravels implies one or more earlier episodes of vulcanism in the region.

Cyclic erosion surfaces exemplified by gravel-strewn pediments abutting against the north and south sides of Barilla and Johnson mesas, respectively, at approximately corresponding levels test the probability of not less than three periods of stabilization of the progressively lowered base level.

Lithologic similarities evidenced by pebble counts of the high-level gravels and those of Pliocene Ogallala age to the east and south demonstrate a common source area in the mountains to the west. Westward projection of the base of the Ogallala to the mesa area implies the presence of a highland in the area during Ogallala time. On this basis, the high-level lavas are tentatively dated as Miocene or early Pliocene instead of Quaternary as formerly supposed.

LIMESTONE A SOURCE ROCK OF PETROLEUM

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The most likely source rocks of petroleum are those highest in original organic content. The clastic or mineralogical content of the rock has very little to do with the formation of oil. Limestone with a high organic content may contain as much petroleum source material as an organic shale. Therefore, organic limestones must be considered source rocks of petroleum.

Recent studies disclose that most highly organic sediments are deposited in stagnant, deoxidized basins where organic decomposition is inhibited by the toxic environment of quiet bottom water. Such an environment is apparently tolerant to the precipitation of limestone. Highly organic marls accumulate today in stagnant basins.

The regular lateral gradation from coarse to fine texture in many ancient sediments is similar to the gradation of sediments in modern stagnant basins. This regularity is in sharp contrast to the irregular distribution of sediments of modern continental shelves where currents are vigorous and the water well aerated. These conditions on the continental shelf are not conducive to organic preservation, which leads to the conclusion that the evenly graded organic sediments of the past (*e.g.*, parts of the Upper Cretaceous) were deposited in environments similar to those in modern stagnant basins.

Parts of the limestone sections in the Middle East and the Maracaibo Basin are typical stagnant basin deposits and are the only conceivable source rocks of great quantities of oil. The Sunniland field in Florida produces from the middle of a limestone section 20,000 feet thick, where limestone is the only obvious source rock.

PEDIMENTS AND PEDIPLAINS

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Pediments, described by W J McGee in 1897, have been established by usage as rock-cut surfaces flanking mountain bases of arid regions. Seeking a term for low-relief regional surfaces of arid erosion exemplified in the Mohave Desert, California, the writer with George H. Anderson in 1935 defined "pediplain" as a "widely extending rock-cut and alluviated surface . . . formed by the coalescence of a number of pediments and occasional desert domes" and pointed out that pediplains are not restricted to old age of the arid cycle. Instead, successive stages from youth to old age are characterized by continually increasing ratio of area of pediplain to area of residual mountains. In 1942 Arthur D Howard proposed that a term of modified spelling, "pediplane", be used for "degradational piedmont surfaces produced in arid climates which are either exposed or covered by a veneer of contemporary alluvium no thicker than that which can be moved during floods". This is the presently ac-

cepted definition of "pediment". Howard's "peripediment" is a special type of pediment eroded on a basin fill. The writer believes that "pediplain" should be retained as originally defined for the regional surface formed by coalescence and near-coalescence of pediments together with intervening alluviated areas if present, by junction of pediments (even though they are discordant) through pediment passes, and extending over desert domes even though they are higher than the general surface.

ISOPACH STUDIES IN ARIZONA AND ADJOINING AREAS

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Isopach maps representing periods of the Paleozoic and Mesozoic have been prepared for Arizona and adjoining areas and indicate certain structural trends that controlled deposition within the region throughout Paleozoic time and certain major changes that developed during the Mesozoic era.

Two stable domes—the Defiance in northeastern Arizona and Ensenada near the southwestern corner—appear to have influenced distribution of sediments throughout Paleozoic time, although they apparently contributed little detrital matter. The Cordilleran geosyncline to the northwest and the Sonoran geosyncline to the southeast, major belts of sedimentation, extended into and at times were connected across a less negative belt termed the Arizona sag.

Changes in the basic pattern of structural control were few in early and middle Paleozoic time. During late Paleozoic, however, total sedimentation was relatively greater in all areas, and some notably deep basins developed. Uplift of the Uncompahgre highlands of southwestern Colorado was responsible for thick detrital deposits accumulating near by.

In Mesozoic time fundamental changes in structure pattern developed. Triassic uplift in central and southern Arizona caused withdrawal of the seas. Disturbances at the close of the Jurassic destroyed the Cordilleran geosyncline; southern Arizona was uplifted and eroded. In both Lower and Upper Cretaceous thick deposits of sediments and volcanics filled a trough from Sonora across southern Arizona. In Upper Cretaceous, also, a seaway from the east covered northern Arizona.

A composite map of total Paleozoic deposits illustrates the basic structural controls in Arizona. Another, combining all Paleozoic and Mesozoic deposits, emphasizes the many changes in pattern that developed during Mesozoic time.

CENOZOIC GEOMORPHIC HISTORY OF THE OAK CREEK CANYON REGION, ARIZONA

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Oak Creek Canyon, a 12-mile erosional gash in the southern rim of the Colorado Plateau, is excavated along a generally north-trending Pliocene fault to a point 13 miles south of Flagstaff, Arizona. The stratigraphic section exposed is generally similar to the upper portion of the classic section in Grand Canyon, ranging from Mississippian Redwall limestone to Triassic Moenkopi red beds. Miocene gravels and Pliocene basalt complete the section.

Cenozoic geomorphic history is related to uplift of the southern Colorado Plateau from a low elevation to its present height of 6000 to 7000 feet above sea level. Episodes include: (1) Uplift of the Plateau; Erosion, producing a surface of 200 feet relief (Miocene), (2) development of a higher mountain block to the south (Miocene), (3) Deposition of gravels containing Precambrian fragments derived from mountains to the south (Miocene), (4) Faulting, high-angle tensional type (Pliocene), (5) Erosion of fault blocks (Pliocene), (6) Vulcanism, basalt inundating previous topography (Pliocene), (7) Faulting, represented by the present Oak Creek fault (Pliocene), (8) Erosion, forming present canyon; downcutting in several stages (Pleistocene to Recent).

The present course of Oak Creek is independent of the main fault crush zone although both trend southward through the canyon bottom. The creek deviates from the upthrown fault scarp where talus protected the fault plane, and where the lava surface on the downthrown side of the fault locally sloped away from the fault.

STRUCTURE AND PRE-PENNSYLVANIAN STRATIGRAPHY OF THE WELLSVILLE AREA, COLORADO

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This study of the Wellsville area, which lies on the north flank of the Sangre de Cristo Mountains near Salida, Colorado, makes available an accurate detailed, stratigraphic section of early Paleozoic rocks and an areal map of the structural features.

The detailed section, based on field and microscopic studies, involves the following units: Manitou, 197 feet of banded, cherty dolomite; Harding, 65 feet of well-bedded quartzite; and the Fremont, 229 feet of massive dark-gray crystalline dolomite, all of Ordovician age; the Devonian Chaffee formation containing two members, the Parting which consists of two lithologic types, 25 feet of shaly dolomite limestone and 29 feet of coarse quartzite, and the Dyer, 92 feet of buff cherty dolomite; and the Mississippian Madison formation, 238 feet of black to dark-gray, massive to thin-bedded limestone.

The area is the probable focal point of forces acting on or originating in the Sawatch, Mosquito, and Sangre de Cristo ranges. The complex structure may be mapped in three groups: northwest-trending thrust faults of moderate dip, asymmetric folds paralleling the thrust faults, and vertical shear faults which trend west-northwest at approximately 45° to the folds and thrust faults. Observed slip along the thrust planes trends approximately N.10°E. Each asymmetric fold seems genetically related to one or more thrust faults. The displacement along the vertical shear faults is oblique slip with a dominant horizontal component of movement. In each vertical shear fault the northern block is displaced upward and eastward. A study of these structural relations suggests: (1) that nearly oppositely directed compressive forces applied from the northeast and southwest produced the thrust faults and folds; (2) that later, renewed forces applied from the west and southeast produced a couple which moved the north part of the area relatively eastward.

PETROGRAPHIC STUDY OF TOOTH DECAY*

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Sections of teeth were studied to determine the effectiveness of the Gottlieb treatment. First the teeth were treated with zinc chloride and potassium ferrocyanide as outlined by Gottlieb, Stebner, and Gowan. Subsequent staining with ferric chloride produced a deep blue color in the earlier precipitated chemical. The teeth were then sectioned by ordinary petrographic methods. Petrographic examination shows the depth of penetration of the chemicals and extent to which lamellae are plugged. The relation of lamellae to tooth decay is clearly brought out.

STRATIGRAPHIC PROBLEMS IN THE DUCHESNE RIVER VALLEY, UTAH

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On the North Fork of the Duchesne River, on the south limb of the Unita Mountain anticline, a massive, light-yellow to brown sandstone, with some quartzitic and arkosic beds, is exposed.

In 1907, F. B. Weeks correlated the formation with the Ogden quartzite. In 1937, Forrester proposed the name Pine Valley quartzite and suggested its age as probably Cambrian. If the Pine Valley quartzite is Cambrian, the Cambrian sedimentary sequence on the Duchesne River differs from the usual Cambrian sequence in Utah and calls for an explanation.

In the Tabiona area in the Duchesne River Valley a thick formation is exposed that is variegated in color and in its lithologic characteristics.

In 1912 C. T. Lupton gave the thickness of the formation as 10,000 feet and called it Wasatch; and in 1934 J. L. Kay mapped it as Duchesne River. In 1939 the writer began the study of the formation and in 1940 concluded that it is younger than late Montana and older than the Duchesne River formation. In 1944, C. T. Walton named it Currant Creek, gave its age as probably late Upper Cretaceous and its measured thickness on Red Creek as 4550 feet

* Graduate School Project, University of Wyoming.

In the writer's opinion, it is probably Paleocene and in the Duchesne River Valley has a measurable thickness of more than 9000 feet with the top not exposed.

PERMIAN (?), TRIASSIC, AND JURASSIC STRATIGRAPHY OF THE McCOY AREA, WEST-CENTRAL COLORADO

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This study deals with stratigraphy and sedimentation of the Permo-Triassic "red beds" and related formations of the McCoy area in west-central Colorado. Except for the lower part, detailed work has not been done previously on this section. Detailed sections are measured and correlated in the field. Specimens are examined microscopically. Regional relationships are presented by means of correlated columnar sections and isometric fence diagrams.

All formations thin to the northeast against the Front Range positive element. Permian (?) rocks coarsen northeastward. All rocks show distinct genetic relationships either to the Front Range or Uncompahgre positive element.

The Pennsylvanian or Permian "Schoolhouse sandstone", a cross-bedded, fine-grained, gray, quartzitic sandstone, probably of beach origin, overlies Pennsylvanian arkoses and siltstones. The Permian (?) State Bridge formation overlies the "Schoolhouse sandstone" or, in some places, Pennsylvanian arkoses. The State Bridge consists of brick-red sandstones, siltstones, shales, and a central limestone member. Graywacke facies and gypseous facies are present in basal State Bridge. Basal Shinarump conglomerate rests unconformably on the State Bridge. This formation, which consists of coarse, cross-bedded, quartzitic sandstone and lenticular conglomerate, grades upward into the Chinle formation. The Chinle is composed of deep-red, lenticular sandstones, mudstones, siltstones and shales, and lenticular intraformational limestone pebble conglomerate. The overlying and unconformable Entrada sandstone is eolian, cross-bedded, fine-grained, salmon pink or buff. Above this is the marine Curtis formation, a gray, oölitic, fossiliferous sandstone or sandy limestone.

The "red beds" are of continental origin. State Bridge material probably was derived from the Front Range element, Chinle from the Uncompahgre element.

EARLY CRETACEOUS SEDIMENTS IN EASTERN UTAH

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Early Cretaceous sediments have been assumed to be absent in eastern Utah and adjoining areas since 1933 when Baker, Dane, and Reeside (U.S.G.S. Professional Paper 183) transferred the Morrison formation from the Cretaceous to the Jurassic. The unconformity at the base of the Dakota (?) therefore has been regarded as representing the whole of early Cretaceous time. The Morrison faunas considered by various writers as indicating Jurassic age have all been obtained from the lower two-thirds of the formation leaving above a thin but widespread unit of doubtful affinities included with the Morrison mainly because of lithologic similarity. Recent collections of plants and microfossils from this unit in eastern Utah and western Colorado contain significant elements known elsewhere only from early Cretaceous beds. Charophyte and ostracod remains suggest correlation with the Trinity group, Kootenai formation, and upper part of the Gannett group. It is believed that this unit can be mapped separately so that the Jurassic-Cretaceous boundary need not fall at some indefinite place in the Morrison. This interpretation brings the eastern Utah-western Colorado section into agreement with adjacent areas where Lower Cretaceous formations have long been recognized.

GEOLOGIC MAPPING OF TUNNELS FOR ENGINEERING USE

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Detailed geologic study and mapping of tunnels constructed in the past has often been neglected. The design and construction of tunnels would benefit greatly if some standardized system of geologic mapping were adopted for all tunnels and results made available along with construction records. Some of the benefits derived from tunnel mapping are: correlation of rock condition and type with support requirements, wider recognition of tunnel problems of geologic origin, correlation of water seepage in the tunnel with ground-water behavior, comparison of surface geologic data with tunnel

conditions for guidance in subsequent preconstruction surface mapping on other tunnels, and valuable aid in operation and maintenance when difficulties involving geologic conditions are encountered.

The Bureau of Reclamation is developing procedures for studying and recording tunnel geology which the writer believes would make a good basis for general standardization. In Bureau of Reclamation tunnels, all ground-water conditions and significantly different geologic structures and rock types are identified and described including the location, spacing, attitude, tightness, or cementation of faults and joint systems; location and extent of overbreak is recorded; record samples are secured representing all major formations and conditions enountered during construction with special attention to the correlation of actual tunnel conditions with preconstruction interpretations. These data are assembled from day-to-day records on a plan and two side views of the tunnel, using charts developed for that purpose; the traces of faults, formations, contacts, etc., are shown as actually exposed on the curved tunnel walls and back.

PETROCHEMICAL STUDIES OF ALKALINE ROCKS, MOROTU DISTRICT, SAKHALIN

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Remarkable types of alkaline rocks in the Morotu District of the northwestern coast of southern Sakhalin form intrusive bodies, such as dikes, sheets, or small laccoliths, intruded into the coal-bearing Miocene formations. They display very clearly various modes of differentiation *in situ*; the marginal parts are composed of basic facies of trachybasalts and trachydolerites, while the central parts consist of monzonitic or syenitic facies, with gradual boundaries. Thus they form typical differentiated intrusions. Though feldspathoids are absent, the mineralogy of these rocks is rather complicated; the basic rocks have abundant crystals of biotite as chief mafic mineral, while the syenitic rocks are characterized by such alkalic minerals as aegirine, aenigmatite, arfvedsonite, and albite. By the use of numerous chemical analyses of the rocks and of the rock-forming minerals, the course of differentiation of the original magma and the stability relations of the rock-forming minerals are shown. The original magma is considered to be slightly alkalic "olivine basalt magma type," rather rich in hyperfusible constituents, which played an important role in the later stage of crystallization, especially in the formation of the syenitic rocks. The abundant crystals of analcite in the leucocratic facies may be considered as the substitute for feldspathoids under the influence of hyperfusibles. Thus the crystallization proceeded continuously from the orthomagmatic, to the pneumatolytic, and to the so-called "hydrothermal" stages.

GEOLOGY OF THE EAST FLANK OF THE BIGHORN MOUNTAINS NEAR DAYTON, WYOMING

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The geology of an area north and south of Tongue River, Wyoming, is described. The Precambrian core of the Bighorn Mountains is composed mainly of variable granite. Strata of all geologic periods except Silurian and Devonian are represented. Stratigraphy and structure are discussed. Petrologic data derived from thin sections are correlated with stratigraphy. Flatirons, high ridges, and deeply incised canyons create a rugged topography with a maximum relief of 4000 feet. Dissected pediment surfaces at different elevations truncate Paleozoic, Mesozoic, and Tertiary strata.

PROBLEMS OF THE WELLS AND BRAZER FORMATIONS IN SOUTHEASTERN IDAHO*

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In the Slug Creek quadrangle and adjacent parts of Caribou and Bear Lake counties, southeastern Idaho, the contact between the Pennsylvanian Wells and Permian Phosphoria formations is a problem. Formerly the contact was considered conformable and gradational. Detailed mapping suggests an unconformity 75 feet below the present Wells and Phosphoria contact that may be the contact between Pennsylvanian and Permian strata.

Another problem is the absence of a mappable contact between the lower part of the Wells formation, which contains fusulinids, and the underlying strata containing corals characteristic of the Mississippian Brazer limestone. The Wells and Brazer formations are lithologically similar, and the lithology, particularly of the Wells, varies laterally. Detailed faunal studies and mapping will be necessary to separate the two formations.

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ABSTRACTS OF PAPERS PRESENTED AT THE MEETING OF SECTION E, AAAS, IN CLEVELAND, OHIO, DECEMBER 27–29, 1950

MINERAL RESOURCES OF ANGOLA (PORTUGUESE WEST AFRICA)

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Of the two Portuguese colonies in Africa, Angola, or Portuguese West Africa, has produced the greatest share of mineral wealth. It is best known for its diamond ouput, in which Angola ranks fourth among the top diamond-producing countries; production of copper, gold, manganese, and rock salt is also recorded.

The regional geology is briefly reviewed, and the geology of the principal mineralized districts is described. The alluvial diamond deposits along the southern tributaries to the Kasai River are the major source of Angola's diamond production. The distribution of the diamond-bearing gravels is outlined, and possible source areas are noted.

Recent development of deposits of nonmetallic minerals, including mica and other pegmatite minerals, lignite, and associated coals of bituminous grade, and rock salt, are reviewed.

Statistics of mineral production for a 10-year period, 1939 through 1948, are given. Notable trends in mining activity and potentially valuable areas for prospecting are listed. A complete bibliography of the most recent authoritative papers is also given.

CATALOGUE OF ROCK ANALYSES

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Arrangement of the rocks is based upon chemical composition and is denoted by a double index number. The first index gives alumina, alkalies, lime, and ferromagnesia; the second index gives silica, ratio of potash to total alkalies, and ratio of magnesia to total ferromagnesia. Since the system is particularly adapted to graphic representation, genetic relationships between rocks and rock families are demonstrated effectively.

GEOLOGY OF THE CLEVELAND REGION: SUMMARY

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The Cleveland region is underlain by horizontal sedimentary strata of Ordovician to Pennsylvanian age. The surface features of the region are the product of Mesozoic and Tertiary regional uplifts and stream erosion, followed by Pleistocene ice invasions and the subsequent shoreline activities of the glacial lakes. Mineral resources are clay, building stone, salt, gas, sand, and gravel.

SUBSURFACE STUDY OF GLACIAL DEPOSITS AT CLEVELAND, OHIO

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The writer has studied a number of soil borings drilled to bedrock within a localized area along the Cuyahoga River in the central part of Cleveland, in an effort to correlate the materials encountered and assign them to the geologic processes concerned. The materials examined were continuous samples of soil from the borings. Many of the soil samples were given laboratory tests; all were assigned complete physical descriptions.

From the study a definite pattern was obtained, having layers of stratified lacustrine clays and silts alternating with layers of distinct glacial till. Between the surface alluvium and bedrock, four layers of till are identified, with intervening layers of lacustrine deposit. These layers extend laterally with reasonable consistency through all the borings studies (spread over an area perhaps a mile in length) and can confidently be assigned to four separate advances over the Cleveland area by ice sheets of the Pleistocene Epoch. The three uppermost layers of glacial till are probably prod-

ucts of the Wisconsin ice sheet. The fourth and lowest may be of Illinoisan origin, although proof is not attempted in this study.

TERRE HAUTE, INDIANA, AND ITS NEIGHBORS

Thomas Frank Barton
Bloomington, Ind.

The objective of this paper is (1) to describe the growth by decades of Terre Haute and its neighbors; (2) to present geographic reasons which partially explain this growth; and (3) to give a perspective which should be available to those planning for the future of Terre Haute and/or its area.

This city's most rapid growth took place between 1900 and 1910 when the population increased from 36,673 to 58,157. Its population reached a peak of 66,083 in 1920 and then declined to 62,810 in 1930 and 62,693 in 1940. These statistics bring up several questions. Why did the city grow so rapidly between 1900 and 1910? What factors contributed to the decline between 1920 and 1940? What will the 1950 census show concerning its growth? What are the prospects for future growth?

Perhaps in the past too many people economically and academically interested in Terre Haute's growth concentrated their attention on the political city and failed to give adequate consideration to its relative location and its neighbors.

Terre Haute is about 163 miles south of Chicago and 100 miles north of Evansville, Indiana. Seventy-three miles to the northeast is Indianapolis, the capital, central hub of the state's transportation system, and one of the most rapidly growing cities in Indiana. Within approximately 1½ hours drive or about 60 miles from Terre Haute is a group of smaller cities which have continued to grow.

From the standpoint of method, the writer believes that, in studying a city, increased attention should be given to the city's neighbors. In fact, more geographic urban studies should treat the common development of cities and villages within an area.

ALGOMA STEEL PLANT: A CASE STUDY IN THE THEORY OF INDUSTRIAL LOCATION

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The degree of concentration of Canada's steelmaking capacity in the Sault Ste. Marie plant of the Algoma Steel Corporation Ltd. challenges geographical thinking. One of three integrated steel plants, its capacities account for 49 per cent of the nation's coke, 38 per cent of the pig iron, 27 per cent of the open-hearth steel, and 24 per cent of the finished hot rolled steel. The location stands in contrast to the locations characteristic of steel plants in the United States. It is remote from Canadian centers of industry, population, and coal supply. Its fuel moves toward iron ore and away from the major market.

Coals from Alberta and Nova Scotia are economical. Supplies from owned properties in West Virginia permit the production and sale of extra coke to industry in the mining region of Northern Ontario.

One fifth of the iron ore is supplied by a near-by owned mine. Low in iron, but high in manganese, it is extracted and beneficiated at relatively low cost. Michipicoten sinter enables the use of more than normal portions of low-cost fines. Profits from the mining operations strengthen the corporate financial position.

Insofar as the raw-material factor affects the success of the plant, it provides a favorable base for steel making behind the Canadian tariff wall.

Adjustments tend to offset the remoteness of the plant. Production is concentrated in diversified semifinished steel products, which command higher value than pig iron but enjoy lower freight rates than more highly finished steel products. Rails are an important exception. The small size of the potential Canadian market limits the number of competing plants. Since no single plant can afford to install all the equipment necessary to fulfill total Canadian demands, the Sault Ste. Marie plant may expect to continue servicing phases of the Canadian market at present levels.

Much of the success of the plant is due to the constructive financial policy of plowing total earnings back into the business for 15 years to expand and diversify productive capacity. Since 1935, earnings have progressively increased, and financial position has greatly strengthened. The effect of these policies is reflected in greater and more consistent utilization of capacity, steadily increasing production, and the important position of the corporation in the Canadian national economy.

GEOGRAPHICAL STRUCTURE OF THE OHIO EDISON COMPANY: A PRIVATELY OWNED ELECTRICAL PUBLIC UTILITY SYSTEM

James R. Beck
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The Ohio Edison electrical utility system derives a distinctive geographical structure from localization of physical facilities and adjustment of operational practices to a distinctive pattern of market demand which permit differential costs and the generation and supply of energy to centers of demand.

Although the system serves an area of only 9754 square miles in Ohio and Pennsylvania, with a population of 1,750,000, it produced and sold in 1949 over 4 billion kwh., or more than half as much as the total for all South America, and derived a gross income exceeding $75,000,000. Extensive industrial and commercial usage and high per-capita domestic use are factors.

Analyses of locational factors and operational practices at each of 14 generating stations reveal distinct individuality resulting from the interplay of differential coal and transmission costs and limitations of local water supplies. Twelve stations lie within the consuming area, probably to be expanded to serve future local needs and cost advantage. Eight will not be expanded since they possess neither cost advantage nor water supplies. Two plants are located on the Ohio River outside the service area. These are the largest and newest and together have 44 per cent of the generating capacity of the system. Despite water-borne coal, the cost of transmission to most of the market area is high. The development of the Ohio River plants reflects water shortages within the marketing areas. The system of 14 dispersed plants is economical.

Analyses of transmission systems, local distributional systems and maintenance, and commercial and managerial bases show the total geographic structure.

CINCINNATI ENVIRONS: LABORATORY OPPORTUNITIES FOR A REALISTIC STUDY OF PHYSICAL AND CULTURAL GEOGRAPHY

Melba Phillips Bowers
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The Cincinnati area offers many and varied opportunities for observations of both physical and cultural geography. A realistic approach through field trips is thereby afforded. Through color transparencies, illustrations of man's use of environment, as well as important features of the environment, can be preserved for lectures, rainy-day use, or even for exchange with instructors in other localities. Trips of varying length from 1 hour to an all-day 150-mile round trip in the tri-state area within a radius of 85 miles of Cincinnati have furnished rich hours of field work for student and instructor.

Situated near the southern limit of glaciation, the Cincinnati environs offer excellent examples of a terminal moraine, kames, filled valleys, abandoned valleys, and outwash plains.

An annual rainfall of nearly 40 inches brings about many illustrations of land conditions caused by the erosion and deposition of running water, sheet wash, and slump. Smogs, snow and sleet storms, and occasional tornadic winds offer dramatic examples of weather changes—especially if a field trip begins in a thunderstorm or feels its way through an early-morning fog.

Several streams enter the Ohio near Cincinnati and, with the mature topography of the postglacial Ohio valley and near-by northern Kentucky hills, present many interesting and graphic relief contrasts. From the flat Clermont County Illinoian outwash plains, still little dissected, to the unglaciated Kentucky areas a wide variety of erosional stages, of terraces, alluvial fans, talus slopes, and flood plains lies before the observant student.

On this natural stage setting, furnished with adequate resources of ground water, soil, gravels, and the Ohio River, man has been busy. His patterns of life, evidenced in the architectural styles, street names and arrangements show cultural influences of German, English, French, and even Swiss societies. Industry, transportation patterns, and residential distributions all show arresting correlations with the geographic backdrop.

PEDOLOGICAL AND GEOLOGICAL CONNOTATIONS IN INDIANA

T. M. Bushnell

This paper discusses soils as functions of heredity, environment, and age, or, expressed in expanded form, of parent materials, climate, biological factors, water regime and time. Materials and time are directly connected with geology, which also may be involved in the climatic and topographic components interrelated with water regime. Thus every soil condition or separation must have various geological connotations.

Fifty years of Soil Survey in Indiana have amassed extensive data by detailed or reconnaissance mapping and by special or miscellaneous studies. Findings are published in Soil Survey reports, *The story of Indiana soils*, and special papers. Specific examples are cited from these sources, or unpublished studies, of geological aspects of Indiana soils such as the following:

(1) Sedimentary bedrock formations as soil-forming materials: their patterns, slopes, ages, and related terrace or alluvial deposits.

(2) Features of glacial drift, including land forms, ages, textures, proportions of local and exotic rocks, assorted and unassorted, shallow and deep, and related deposits reworked by water or wind.

(3) Features of loess (wind-laid silts) including patterns, sources, ages, composition, thickness, and textures.

GEOGRAPHER IN SCANDINAVIA

Lucile Carlson
Western Reserve University, Cleveland, Ohio

Observations and impressions of the geography, culture, and political conditions of Denmark, Norway, and Sweden will be related and illustrated with kodachrome slides. The six weeks' trip of travel and research taken during the summer of 1950 included much of Denmark, Sweden from Malmo in the south to Kiruna beyond the Arctic Circle, and Norway from Narvik to Oslo. The southward journey through Norway was made by boat along the fjorded coast from Ofotfjorden to Trondheim.

NARVIK, NORWAY: SWEDISH ORE PORT

Lucile Carlson
Western Reserve University, Cleveland, Ohio

Until the first train to Narvik, in 1902, brought iron ore to its harbor for shipment from the Luossavaara-Kirunavaara fields in northern Sweden, only two or three very poor families lived there. The city today has a population of approximately 14,000 solely because of the Swedish mining industry.

Narvik (68.20° N. lat.) lies 250 kilometers from the last lighthouse, at a point of land where two fiords meet. It is too far from the open coast and from normal trade routes to be a general port or a port-of-call, and the fiord waters are too cold and deep for fish. Banks farther out were formerly used by some fishermen for the seasonal herring catch, but today Narvik does no fishing. Its function is to export ore. Importing is limited to small amounts of coal and other living necessities for local consumption.

Following the April 9, 1940, attack by the Germans, the ore docks were destroyed; today they are restored to their former capacity and, within 6 months, will be fitted to handle greater tonnage.

Monthly exports of ore do not depend upon the season, as generally thought. Narvik does not act as the winter outlet to replace Lulea when that port is ice-bound. In 1949, from May through

September, shipments of ore were considerably greater than during the remainder of the year. There is no patterned graph of shipments by months.

Exports to various countries differ from year to year, especially since the war. Previous to 1940, German and England were the largest buyers. Today Belgium, apparently benefiting from the political situation, is the heaviest purchaser.

Swedish boats carry most of the ore; Norwegian ships generally rank second.

EROSION SURFACES OF THE ADIRONDACKS

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The erosional history of the Adirondacks is comparable to that of the Appalachian region. The Precambrian peneplain on the margins of the province is levelled by erosion surfaces which extend across both the eastern exhumed fault-block mountains and the western piedmont area where faulting is almost absent. From oldest to youngest, the Big Moose and Childwold peneplains and the Mohawk and Albany strath terraces are correlated respectively with the Upland, Schooley, Harrisburg, and Somerville peneplains of the Appalachian region.

PROGRAM OF THE AMERICAN GEOLOGICAL INSTITUTE

David M. Delo
American Geological Institute, 2101 Constitution Ave., Washington, D.C.

The American Geological Institute was formally organized in November 1948 and began operation on July 1, 1949. Its establishment came after several years of discussion and resulted from the need of the geological professions for a single mechanism through which they could take unified action. The Institute was organized as an agency of the National Research Council, with the assistance of the Council, and its offices are located in the NAS-NRC Building, 2101 Constitution Ave., N.W., Washington 25, D. C.

The program of the Institute is devoted to (1) professional services to the geological professions, and (2) co-operation with groups and individuals interested in various branches of geology in a non-professional way. A very large amount of the attention of the Institute is now devoted to the current war emergency, aimed particularly at the effective utilization of earth science and earth scientists to the maximum benefit of the country. A program relating to the role of earth science at all levels of education is also an important part of Institute activities.

PLEISTOCENE STUDIES OF THE U. S. GEOLOGICAL SURVEY AND THEIR RELATION TO SOILS*

Charles S. Denny
U. S. Geological Survey, Washington, D. C.

The U. S. Geological Survey is conducting extensive studies of the Pleistocene geology of areas widely scattered throughout the United States. The detailed mapping of surficial deposits is yielding fundamental data on the nature and origin of soil parent materials and is unraveling the events of Pleistocene and later times, especially the climatic history and the resulting changes in the processes of weathering, erosion, and deposition. The geologist is impressed with the apparent differences in soils on geologic parent materials of diverse age and origin, and suspects that the soil differences are related to events of Quaternary time. Soil profiles, both buried and on the present land surface, are probably one tool for the correlation of deposits and land surfaces over wide areas.

Pleistocene deposits in Potter County, Pennsylvania, are being studied in informal collaboration with soil scientists. Small and widely scattered remnants of a soil of the Sangamon or last interglacial stage are found in the nonglaciated portion of the county. The outstanding characteristic

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of the unglaciated portion of the county, however, is the widespread occurrence of a surficial mantle of unconsolidated debris of Wisconsin age. This mantle is called a congeliturbate. The term "congeliturbate" refers here to debris produced by intense frost weathering of the bedrock and of the Sangamon soil, and the movement of such material by solifluction down the long, smooth, and, in places, very gentle slopes so characteristic of the county.

SOME GEOLOGIC FEATURES OBSERVED ON A MOTOR TRIP THROUGH AFRICA FROM ALGIERS TO CAPE TOWN

Henry F. Donner
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The general geologic features of the African continent encountered on the Algiers to Cape Town trip will be described and illustrated with Kodachrome slides and maps. These features include the folded mountains in the extreme north and south; both sandy and rocky phases of the Sahara Desert; and the volcanic region and Great Rift Valleys of Central Africa. The geologic setting of the gold and diamond mines in South Africa will be described, and specimens from these mines will be available for inspection.

OCCURRENCE OF THE MIDDLE DEVONIAN COLUMBUS LIMESTONE NEAR INGERSOLL, ONTARIO

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Fifteen feet of very fossiliferous limestone, containing *Paraspirifer acuminatus* (Conrad) and other fossils indicative of the Columbus limestone, are present in Chemical Lime Company quarry in the Thames River valley 1.3 miles east of Ingersoll, Ontario. The basal part of the Columbus limestone at this locality consists of 1 to 2 feet of calcareous sandstone, which rests disconformably on 38 feet of very pure limestone of Detroit River age.

This occurrence of the Columbus limestone is about 100 miles east and 85 miles north of Pelee Island, Lake Erie, on which is present the northernmost exposures of the formation heretofore described.

Only the upper part of the Columbus limestone is present in the Ingersoll region. Progressively older strata of the formation have been recognized in outcrop and deep wells in passing southwestward from the Ingersoll region to Columbus, Ohio.

SUBSURFACE STRATIGRAPHIC SECTIONS ACROSS THE NORTHERN PART OF THE APPALACHIAN BASIN

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Twelve subsurface stratigraphic sections obtained by the examination of drill-cutting samples from deep wells have been selected for presentation. The wells start in strata of Devonian or later age and penetrate either the Cambrian or the Precambrian. They are located in a belt which starts on the Findlay arch in northwestern Ohio and southeastern Michigan and extends northeastward south of Lakes Erie and Ontario to the southwest flank of the Adirondack Mountains in east-central New York. The belt lies well up on the northwest limb of the Appalachian synclinorium.

Among correlation problems to be discussed is the probable Cambrian age of the dolomitic sandstones and sandy dolomites at or near the unconformity at the base of the Black River limestone in northern Ohio and northwestern Pennsylvania which have been referred to the St. Peter sandstone. The possibilities of the deeper formations as potential sources of oil and gas will be discussed briefly.

SOIL-FORMING INTERVALS EVIDENCED IN THE KANSAS PLEISTOCENE

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Pleistocene deposits in Kansas record cyclic sequences of erosion, sedimentation, and essential equilibrium. During equilibrium intervals soil formation was dominant, and erosion and sedimentation were regionally insignificant. In the relatively shorter erosion and sedimentation intervals soil was destroyed or buried. Stratigraphic and paleontological studies during the past decade make possible correlation of the cyclic episodes in the Kansas Pleistocene with the glacial sequence to the northeast and of the intervals of soil formation with interglacial intervals.

In Kansas the earliest Pleistocene soil may have developed on the Pliocene alluvial plain and coextensive erosion surfaces. Cycles of erosion and sedimentation were produced by the events accompanying Nebraskan and Kansan glaciation of northeastern Kansas, whereas soils (now destroyed or buried) were formed during Aftonian and Yarmouthian interglacial intervals.

Late Pleistocene glaciers were more remote from Kansas than earlier ones; their effects were less violent but more clearly recorded in the sediments. Illinoian erosion and deposition were prominent in northern Kansas, whereas in southwestern Kansas soil formation locally continued from Yarmouthian through Sangamonian time. The Sangamon (Loveland) soil is the most widely observable fossil soil in the Great Plains region. Early Wisconsinan loess commonly buried the Sangamon soil, and the Brady soil, developed on this loess, was buried locally by late Wisconsinan loess. The relative brevity of Recent time is demonstrated by comparison of the modern profile with the fossil Pleistocene profiles.

NEW DISCOVERIES CONCERNING THE SHARON CONGLOMERATE IN NORTHEASTERN OHIO

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Study of the Sharon conglomerate, the basal Pennsylvanian bed in northeastern Ohio, has been a Geological Survey of Ohio project for several years. A new picture of the nature of this deposit is gradually emerging, the basic points of which now indicate: (1) deposition in a lowland bounded on the east by Mississippian highland now represented by the Grand River Valley; (2) deposition in a deltaic type of deposit of relatively pure sand with scattered pebbles and cross-bedding indicating a northern source; (3) sorting on part of the deltaic plain which concentrated quartz pebbles to give conglomerate belts whose direction confirms the northern source; (4) discovery of quartzite pebbles, sandstone pebbles, rotten limestone pebbles, conglomerate pebbles, and fossils as pebbles which indicate at least a partial sedimentary source instead of the igneous source suggested by the literature. The fossil pebbles are identifiable corals, brachiopods and gastropods which indicate a Middle Devonian age for at least part of the sedimentary source rock.

MINERAL CITY "STRUCTURE"

Henry H. Gray
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Complex structural disturbance of the Pennsylvanian sedimentary rocks near Mineral City and Zoar, Ohio, is interpreted as the result of slumping of partially consolidated sediments into the channel of a stream of Pennsylvanian age and burial by later undisturbed Pennsylvanian sediments.

DUNITE RING-DIKE AT WEBSTER, NORTH CAROLINA

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In the Precambrian gneisses and schists of the mountain region of Western North Carolina is a local structural anomaly, consisting of a dome or anticline plunging at both ends of its axis. The

presence of longitudinal joints parallel to the major axis of the uplift and fanning outward along the edges, a fan of tension joints across the dome, which converge inward and downward, and the persistent outward dip of the dike rocks suggest that the dome was formed by a force acting vertically upward without confining lateral pressures. A ring-dike of dunite was intruded along the flanks of this dome sometime after the formation of the dome but before the final deformation of the area. Pegmatites are abundant and appear to have been intruded along joint planes in the country rock and the dike. They may be divided into two types based on their mode of intrusion: conformable pegmatites that were intruded along foliation planes of the gneiss, and disconformable pegmatites that crosscut the foliation of the gneiss and the dike rocks.

The indices and FeO content of the olivine suggest a crystallization temperature of about 1700°C. A negligible contact effect on the country rock suggests intrusion at a temperature of about 500°-800°C, in a nearly solid state. Evidence of the presence and character of the mineralizers that brought this body in is lacking. The included websterite body in the southwestern end of the ellipse is regarded as a later and more acidic phase of the same magma that produced the dunite.

GROWING ROCK CRYSTAL

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Brush Development Co., 3311 Perkins Ave., Cleveland, Ohio

Quartz has no satisfactory substitute for the control of frequencies of electronic-oscillator circuits. At elevated temperature and pressure, high-quality—well-faced—rock crystal has been grown on etched rhombohedral surfaces. Aqueous sodium carbonate is used as the solvent medium, and broken scrap crystals serve as source of the silica.

GEOLOGICAL CLASSIFICATION OF ALLUVIAL SOILS

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Alluvial soils are developed on sedimentary deposits formed in stream channels and on bordering flood plains. The coarser sediments, commonly sand and gravel, accumulate chiefly in stream channels but typically are covered by finer materials, commonly silt and clay, deposited from overbank flood waters after the channel has shifted by meandering or avulsion. Lateral channel shifting is normal, and the resulting vertical sequence of finer-textured alluvium over a coarser substratum is characteristic of most alluvial soils. Normal stream behavior also produces characteristic lateral variations in the finer-textured top stratum, or vertical accretion blanket, and in the soils formed thereon. The principal genetic types of vertical accretion deposits are (1) ridge-and-swale bars, (2) natural levees, (3) backswamp deposits, (4) filled channels, and (5) distributary splays.

Alluvial terraces, which are normal parts of flood plains left above ordinary overflow when a stream erodes its channel, preserve the typical features of alluvial soils, but subject to modifications from lowered water tables and surface erosion.

Progressive aggradation occurs if a stream receives more sediment than it can transport. This may result only in thickening of the coarser substratum, if meandering and lateral floodplain accretion can keep pace with the channel aggradation; but if meandering is subordinate, the channel may be built up relative to the flood plain, overflows become more frequent, and coarser materials spread over the finer-textured surface soils.

Alluvial soils of smaller valleys in parts of the United States are being greatly modified by accelerated channel erosion and floodplain sedimentation due to the effects of agricultural practices.

BEACH SANDS OF THE MEDITERRANEAN COAST OF EGYPT

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Data on the mechanical analysis and the mineral content of beach sands from the Egyptian Mediterranean coast are presented. The sands are of two principal types. On the west, from Dichkela

to Mersa Matruh, they are mainly composed of pure calcareous oölites with few shell fragments and almost no heavy minerals. East from Dichkela to Rosetta they consist essentially of quartz grains with common shells and an abundance of heavy minerals. Their mode of origin is discussed.

HUMAN OCCUPANCE ON LAKE DAKOTA BED AND ON ADJACENT MORAINE TOPOGRAPHY

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The paper is a product of 3 summers of field studies centering on an old lake bed named Lake Dakota half a century ago.

The human occupance of the area, land uses and changes in uses, and the crop values in census years of the last 50 years compared with present values are topics discussed.

Water supply for home and stock use, climate in relation to agriculture, possible or probable changes if irrigation should come, access to markets for both buying and selling, and possibilities for industries are considered.

Detail studies have been made of selected sample townships, and these make comparative analyses possible. Several types of topography and soils, both on the lake bed and on glacial topography outside the lake bed, have been studied. It is believed that well-marked differences in human occupance in the several townships are related to the different topographies.

GIANT EARTH MOVER

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At their Chieftain Mine No. 20 about 4 miles south of Riley, Indiana, Maumee Colleries have in operation one of the largest drag lines in the world. This huge earth mover was built especially for this mine and has a boom 215 feet long and swings a bucket with a 25-yard capacity. The boom, which extends into space at an angle of 45 degrees, can drop its bucket 120 feet below ground level and dump earth about 60 feet above that level.

The drag line is used exclusively for removing an overburden that averages 57 feet, 7 inches thick. This material is composed of clay, gravelly clay, limestone, and slate in that order from the surface downward. The coal seam which is being uncovered and mined averages 5 feet, 1 inch in thickness. The coal is dug with an electric shovel and then transported by 30-ton trucks to a washer. The latter is located on a railroad spur about 1½ miles from the mine. After being washed and screened the coal is hoisted into a tipple from whence it is loaded into railrad cars to be transported to market.

GLACIAL MARINE LIMIT IN MAINE

By Richard J. Lougee
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A spirit-level survey of deltas and other shore features recording the Glacial marine submergence in Maine shows that the marine limit extends inland to the White Mountains, penetrating the Saco Valley to North Conway and North Chatham, N. H., the Androscoggin Valley to Rumford, the Kennebec Valley to The Forks, and the Penobscot Valley to Abbot Village, Millinocket, and Island Falls, Maine.

Glacial deltas and deltaic eskers in a number of cases record local differences in water level of as much as 9 feet, which are believed to exhibit the range of contemporary tidal changes. Otherwise the unbroken continuity in profile of the shore features from an elevation of 222 feet on Mount Desert to 530 feet near North Chatham and Rumford suggests that the marine limit in Maine is a nearly synchronous water plane which expanded into regions uncovered by the ice during a period of crustal stability, and prior to regional tilting.

GEOLOGY OF MICHIGAN

Helen M. Martin
Michigan Geological Survey, Lansing, Mich.

The geological history of Michigan records the filling of an original granite basin bordering the Canadian Shield. Northwestern bays of the basin were filled with iron-formation sediments uplifted and deformed at the close of Huronian time. Deformation was followed by the Keweenawan lava flows that were later uplifted and eroded bringing near the surface copper-bearing lavas, sands, and conglomerates. During Paleozoic time successive seas flooded and ebbed from the slowly sinking Michigan Basin until by the close of Permian time the Basin was filled with successive strata of bowl-shaped sandstones, limestones, shales, and salt, culminated in the shallow, brackish coal swamp of the Pennsylvanian partly covered by Permian (?) red beds. After approximately 300,000,000 years of erosion, glaciation covered the Basin with a mantle of drift. Ponding of the melt waters between moraines and the ice border produced the Great Lakes.

APPLICATIONS OF GEOLOGY AND SOIL SCIENCE TO HIGHWAY PROBLEMS

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Soil is the foundation material on which highways are built. Each State Highway Department furnishes and applies soil and geological information.

The more common methods of application of soil and geological knowledge are: (1) Pedological system of classification, (2) Bureau of Public Roads classification, (3) Civil Aeronautics Administration, and (4) Engineering Geologic classification.

The Michigan State Highway Department has effectively applied the pedological system. A detailed soil survey shows (1) soil types, (2) depth to water table and to bedrock if at shallow depths, (3) classification of swamp materials, (4) location of borrow, etc. Interpretation of the survey information has been accomplished by furnishing charts of information for each soil series.

Highway construction (embankments) across peat swamp has been grouped into methods depending on depth and types of materials. Swamp materials are either excavated, displaced, or compressed. Granular materials (sand and gravel) are required for back-filling. Loams, clays, and silts are not satisfactory. The character of the material can be determined by laboratory tests.

As grading progresses on construction projects the subgrade is examined, to correct all unsatisfactory subgrade conditions, such as (1) very fine sand and silt, (2) seepage water, and (3) abrupt changes in texture.

Nearly all construction projects require the location of borrow for (1) embankment construction, (2) subbases (granular material only), (3) binder materials for stabilization of loose sand grades and subbases where gravel surfacing is called for, and (4) binder material for the stabilization of gravel surfacing.

Foundation investigations for all bridges are required by most State Highway Departments. Investigations in Michigan require the use of hydraulic boring outfits.

Extensive field investigations and laboratory testing are required on major developments such as the Expressways in Detroit. Longitudinal profile of the Willow Run Expressway, Detroit Industrial Expressway, and Edsel Ford Expressway show geological variations encountered. Normal-size footing was required to support bridges on the plastic, firm, and stiff clay till. The soft clays have a low supporting value; hence, bridges are supported by piling which extends down to hard clay, rock, etc. These soft clays are subject to upheaval in cuts exceeding 17 feet.

INFORMATION SERVICES OF THE OHIO DIVISION OF GEOLOGICAL SURVEY

John H. Melvin
Ohio Division of Geological Survey, Columbus, Ohio

The Ohio Geological Survey as a Division of the new State Department of Natural Resources is accelerating a program inaugurated in 1837. An important part of this program is to make known

the results of its geological investigations, to geologists, those engaged in the mineral industries, and also to the public generally.

This obligation is being met through the publication of special reports and maps, by answering inquiries by letter, telephone, and personal interviews, by public appearances before various organizations, by sponsoring field trips and other conferences, and by encouraging the activities of various societies and groups.

GAPS IN THE LITERATURE OF POPULAR GEOLOGY

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Since the differentiation of popular geology from professional geology in the late nineteenth century, scores of books have been written for the layman. Yet adequate coverage in modern popular works is being approached only in the fields of mineralogy and gemology. Many subjects of interest to the public, such as mountains, caves, and fossil collecting, are meagerly provided with literature; the layman interested in ground water, for example, or in the geology of coasts and beaches, will find practically nothing to read.

RELATIONSHIP OF PERMAFROST TO AGRICULTURE IN THE FAIRBANKS AREA, ALASKA*

Troy L. Péwé
U. S. Geological Survey, Washington, D. C.

Agriculture in arctic and subarctic regions is influenced by permafrost. Two permafrost zones are recognized in the Fairbanks area of central Alaska: (1) the flood plain of the Tanana River, and (2) the adjacent broad gently sloping alluvial fans and colluvial slopes. South-facing hillsides and hilltops lack permafrost.

Zone (1) is underlain by sand and gravel. Permafrost extends to a depth of approximately 200 feet but contains no large ice masses. Nonfrozen areas (talik) are present. A year or two after the ground is cleared for agricultural use the permafrost table is lowered. As a result the chilling effect of the underlying permafrost, which retards plant growth, is largely eliminated, and the excess concentration of moisture in the surface soil drains away. No mounds or pits form in these fields.

Zone (2) is underlain mostly by silt. Permafrost extends to a depth of approximately 175 feet, thinning toward the hills. Many irregular ice masses 10 to 40 feet in diameter are present; some occur in polygonal networks. With the clearing of ground these ice masses begin to melt, and mounds 10 to 30 feet in diameter and 5 feet high may begin to form as early as the second or third year after clearing. Large 10-foot thermokarst pits may form in 3 to 10 years. By 1948 approximately 14 cultivated fields in the area had been abandoned or reduced to pasture because of such surface irregularities.

Absence of permafrost, high insolation, and longer growing season combine to make south-facing hillsides desirable for agricultural use.

LAKE ERIE GEOLOGICAL RESEARCH PROGRAM

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A report is presented on the progress to date of the recently organized Lake Erie Geological Research Program, sponsored jointly by units of the Ohio Department of Natural Resources and the Ohio State University.

Observations on bottom sediments and shoreline processes in the Sandusky Bay area are discussed.

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GLACIAL WATER PLANE IN THE WILLIMANTIC VALLEY OF CONNECTICUT

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A spirit-level survey of glacial deltas in the Thames-Willimantic Valley in Connecticut shows that this valley was flooded by a body of glacial water extending northward without interruption from Long Island Sound into southern Massachusetts. The water plane, which may have been at or close to the sea level of its time, now rises in elevation northward from sea level near New London to 650 feet near Monson, Massachusetts. A differential uplift of at least 18 feet per mile is recorded by the profile of the water plane in northern Connecticut. So great has been the regional tilting that it has caused a shift in location of the height of land at the head of the Willimantic Valley to a point several miles north of the late-Glacial divide.

NORTHERNMOST SPANISH FRONTIER IN CALIFORNIA AS EVIDENCED BY THE DISTRIBUTION OF GEOGRAPHIC NAMES

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Within California several widely divergent cultures have come in contact. The two having the most pronounced influence on the present culture are the Spanish-Mexican and the English-American. One tangible evidence of this culture conflict is apparent in the present-day distribution of Spanish and English geographical names within the State. Since California was first investigated by sea and by the Spaniards, many geographical names are of Spanish origin and are located along the more prominent points along the coast. Later during their land explorations, the Spaniards added many other names to California's map. Following the Gold Rush, Americans retained many of the Spanish names and added others of English origin. The zone of contact between the cultures therefore is marked on the map as the weak northern frontier zone that formed the northern limit of Spanish-Mexican settlements, and the evidence of this zone appears in the intermingling of Spanish and English geographical names, with a northern limit beyond which Spanish names are not in use.

LOESS OF IOWA WITH SOME INTERRELATIONSHIP OF SOILS, GEOLOGY, AND GEOGRAPHY

F. F. Riecken

Loess covers half the land surface of Iowa. The three major loess deposits have different sources. Thickness patterns of each major area are well known. Each loess deposit thins away from the source; the major direction of thinning is southeast. The thinning of the loess of each area is exponential.

The loess deposits are of Wisconsin age. Recent studies indicate the loess of northwestern Iowa is of Tazewell subage; the loess of eastern Iowa seems to be of the Iowan subage. The loess of southwestern and west-central Iowa may include some loess of post-Tazewell subage. Seemingly, each loess deposit is not of one glacial subage, but may be of two or more subages. The relationship of the period of deposition to soil characteristics is not clear, probably because only recently have data been obtained to indicate the complexity of the loess deposits.

Soil-forming factors such as type of vegetation, topography, and climate have caused differences in loess-derived soils in Iowa. The Brunigra (Prairies) and Gray-Brown Podzolic loess-derived soils were formed under prairie and deciduous forest types of vegetation, respectively. The Wiesenhoden and Brunigra soils were formed under prairie vegetation, the former under poorly drained conditions and the latter under conditions of good natural drainage. Within the Prairie or Gray-Brown Podzolic soils the degree of horizon differentiation varies; this cannot be explained by any of the above factors. For example, the Seymour series, a Brunigra soil, has a strongly developed textural B horizon, and the Marshall series, also a Brunigra soil, has a weakly developed textural B horizon. Both series are formed on slightly convex slopes from loess which originated in the Missouri River bottomlands. Thus the Seymour series probably owes its textural B horizon to the fact that the soil has been forming for a longer time, whereas the Marshall series formed from a more recently deposited loess. Other studies on the two other loess deposits indicate that the soils nearest the loess source have the

least-developed textural B horizon, regardless of whether the soil is formed under grass or forest vegetation. It is interpreted that in time the soils with little textural B horizon will develop rather strongly developed B horizons.

Soils formed from one loess deposit may differ widely from another source depending on the character of the various soil-forming factors. The agricultural properties of the various loess-derived soils vary widely. Reasons for these variations and their geographic distribution can be determined, and such knowledge is of great importance to agriculture.

TIME RELATION OF MAGMATIC INTRUSION TO POLYMETAMORPHISM AT PRESTON, CONNECTICUT

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In 1912, G. F. Loughlin proposed the following sequence of geologic events:

(1) Intrusion of the Preston gabbro laccolith into unmetamorphosed sedimentary and pyroclastic rocks followed by contact metamorphism and magmatic differentiation.

(2) Regional metamorphism resulting in the formation of the Putnam gneiss, and synkinematic intrusion of the Sterling porphyritic granite gneiss.

(3) Late-kinematic intrusion of the Sterling alaskite gneiss.

(4) Post-kinematic intrusion of granite pegmatite dikes.

Field and laboratory studies indicate that revision of these conclusions is warranted, and evidence for the following history is presented:

(1) Regional metamorphism of intercalated sedimentary and pyroclastic rocks of unknown age to medium- and high-rank gneisses known as the Putnam gneiss.

(2) Intrusion, magmatic differentiation, and hydrothermal alteration of the Preston gabbro.

(3) Kinetic metamorphism and probably thrust faulting recorded by cataclastic gneisses and west-dipping tabular bodies of mylonite derived from the Putnam gneiss; the gabbro was locally converted to amphibolite.

(4) Folding of the Putnam gneiss west of the Preston gabbro on approximately east-west axes, and possibly reverse faulting toward the south; the folds are open and asymmetrical with north-dipping axial planes.

The magmatic origin of the Sterling gneisses is subject to question. The Sterling granitic gneiss was formed prior to the kinetic metamorphism, but its lower limit in the sequence of events is unknown. The Sterling alaskitic gneiss was probably subjected to kinetic metamorphism, and a sedimentary origin is suggested as a working hypothesis. Granitic pegmatites were produced after kinetic metamorphism, but their time relationship to event (4) is not known.

GEOLOGY AS SCIENCE

G. Winston Sinclair
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The modern curriculum insists that nonspecialist students derive from their science courses not only facts, but also an appreciation of scientific method and attitude. The descriptive sciences do not offer such simple techniques as do those involving experimental work, but there are still ways in which the goal can be reached. An example will be given from physical geology, and from historical, of teaching methods which help the student to meet Geology as a true science and not simply as natural history.

DISTRIBUTION OF WIND-DEPOSITED SOIL MATERIALS IN THE UNITED STATES

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This is a progress report on the work of the National Research Council Committee of five geologists and five soil scientists who have been preparing a map of the wind-laid deposits of the United

States, Canada, and Alaska. The committee consulted at least 100 geologists and soil scientists to obtain expert advice on the character and distribution of eolian deposits of the continent. A large-scale map now under preparation shows (1) loess of Wisconsin glacial age, including the four subdivisions; (2) wind-laid sands, both with and without distinct dune forms; and (3) eolian clay deposits which occur chiefly as low dunes. Units (1) and (2) are the most widespread. The soils of approximately 20 per cent of the United States have loess as a major constituent. Possibly there may be as much as 40,000,000 to 50,000,000 acres of wind-worked sand deposits, the largest areas of which are in Nebraska, Texas, and Arizona. Comparison of maps of eolian deposits and of important crops in the United States shows that loess is a major constituent in the parent soil material of most of the corn and wheat belts in the cotton belt east of the Mississippi River and south of Kentucky, and in the wheat- and kafir-growing areas of the High Plains of Texas and Oklahoma. Small patches of it occur in many of the far-western states. Loess is closely related genetically to the glacial deposits of central United States and to the Palouse region of the northwest, where a large fraction of the loess seemingly was blown from glacial outwash deposits or, in part, directly from glacial till. Probably much of the loess of the western part of the Great Plains was blown from unglaciated upland surfaces and mixed with silt picked up by the wind from flood plains of streams rising in mountain glaciers. The map presumably will be published by some interested agency with the consent of the National Research Council.

INFLUENCE OF WISCONSIN GLACIAL STAGES ON SOIL-GROUP BOUNDARIES IN NORTHEASTERN OHIO*

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Wisconsin glacial-drift sheets of three advances of the Killbuck ice lobe and two of the Grand River lobe have been differentiated in the Allegheny Plateau in northeastern Ohio (Columbiana, Mahoning, Trumbull, Portage, Geauga, Stark, Summit, and Medina counties) during ground-water studies by the U. S. Geological Survey and the Ohio Division of Water. The earliest Wisconsin till, deposited only by the Killbuck lobe so far as is known, is very coarse. It lies in southern Summit County, surrounded by later Wisconsin drift. Its eastern, northern, and western margins coincide approximately with those of an area of coarse Wooster-family soils on the 1938 Conrey-Burrage *Generalized soil map of Ohio.*

The second deposit of Wisconsin drift of both lobes, a sandy to silty-sandy till, extends from the most southerly margin of the Wisconsin drift in Columbiana and Stark counties into southern and eastern Mahoning, central Portage, eastern Summit, and southern Medina counties. The soils are mainly of the Wooster family, except in much of Medina County where they are classified as Rittman and Wadsworth because of the lower sandstone content of the till.

The third advance, of both the Grand River and Killbuck lobes, brought markedly different clay or silty-clay till into most of Trumbull, western Mahoning, and northern and western Medina counties. The extent of this drift as deposited by the Grand River lobe is shown precisely on the Conrey-Burrage map as an area of Ellsworth-Mahoning soils, but that deposited by the Killbuck lobe, especially in Medina County, is not so well shown by the soil map.

The second drift includes all that from the Wisconsin boundary to that just later than the Fort Wayne moraine. The third, or clayey drift, includes deposits of immediately pre-Defiance age, and of Defiance and later age. The Fort Wayne-Defiance time interval must have been much longer than is apparent from the rather close association of these moraines in the Till Plain in Ohio.

POST-WAR CHANGES IN THE POPULATION OF POLAND

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The end of the war witnessed deep changes in Poland's population. German genocide of Polish Jews reduced the population by more than 3,000,000, the number of non-Jewish population killed or missing amounted to another 3,000,000, 2,000,000 of whom were Poles.

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During the war there were many shifts of population carried out by the Germans. Millions of compulsory workers were seized in Poland and taken to Germany. The population was further reduced by deportations to U.S.S.R. Since the end of the war most of the survivors and many of those deported to the U.S.S.R. have returned.

The territorial changes which resulted from the conferences at Yalta and Potsdam have been followed by the shifting of millions of inhabitants. Millions of Germans fled from the Oder basin when the Soviet Army approached. The remainder of the German population has been gradually evacuated.

A large number of Poles who lived in the eastern part of the country, annexed by the U.S.S.R., have been transferred to the Oder basin. A considerable number of Poles from the over-populated regions of central and south Poland also have been transferred to Oder basin.

Relatively small numbers of the Ukranian and White Ruthenian population, who lived in the eastern districts of post-war Poland, have been evacuated to the U.S.S.R.; the remainder are scattered throughout the new Polish territory.

Among the 24,000,000 inhabitants of new Poland there are 23,500,000 Poles (98%), 70,000–80,000 Jews, 100,000 Ukranians, 60,000 White Ruthenians, and 150,000 Germans.

The birthrate exceeds 1% p.a.

ADDENDUM

To *Origin of filled sink structures and circle deposits of Missouri*, by J H. Bretz, pages 789–834

V. T. Allen, in *Mineral composition and origin of flint and diaspore clays* (appendix IV, 58th biennial report, Missouri Geological Survey and Water Resources, 1935) believed (page 21) that initial shallow solutional depressions in the pre-Pennsylvanian land surface, receiving a thicker deposit of clay and localizing the ground water drainage, were "subject to renewed slumping when solution had progressed to the proper stage". Allen found (page 20) a slightly larger proportion of coarse sand grains and the largest amount of heavy mineral grains down the dip of the rim rock of one clay-filled sink. "This supports the inference of an appreciable slope toward the present center of the deposit during deposition".

CORRECTIONS AND EMENDATIONS

Contributors to Volume 61 have been invited to send corrections and emendations to be made in their papers, and the volume has been scanned with some care. Corrections and emendations are as follows:

Page 585, Equation (2), delete second X

588, line 3, *read* $R/\sqrt{4kt}$

line 11, f(r,t), *read* $\bar{f}(r, t)$

590, Equation (24), *read* $T - T_s - \alpha D = [-\alpha' L - (\alpha - \alpha')(D - z)]F(z,t) - (\alpha - \alpha')\bar{h}(t)$

592, Table 10, first column, last line, read $100 - \infty$

595, second column, last line, *for* $r = 0.933$, read $r = 0.993$

617, second column, lines 19 and 20, *for* $13.5P_2$, whence $P_1 = \dfrac{60 \cdot 10^{-13}}{13.5}$

read $13.5 \cdot 10^5 P_2$, whence $P_1 = \dfrac{60 \cdot 10^{-13}}{16.5}$

line 23, *for* $20P_2$, *read* $20 \cdot 10^5 P_2$

695, second column, line 9 from bottom, *insert* many localities *before* southern

697, first column, *heading should read* Distributive Provinces

second column, line 28, *for* 1.791, *read* 1.797

738, first column, line 2 from bottom, *for* scarps bounded, *read* scarp-bounded

848, second column, line 13, *for* $\pm$ .01 μ sec. *read* $\pm$ .10 μ sec.

863, first column, last line, *for* F (Pl. 3), *read* F(Fig. 3)

898, Table 2, thickness of Chorrera Basalt, Verro Gigante Basalt, Bruja Dolerite, etc. is 1000 feet

905, *transfer* paragraph beginning *Alhajuela Formation* to precede paragraph beginning Reeves and Ross (1930)

918, second column, line 2, *for* Tertiary and Cenozoic, *read* Cenozoic

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Yagi, Kenzo: Petrochemical studies of alkaline rocks, Morotu district, Sakhalin ... *1560*
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Yoder, H. S., and Keith, M. L.: Complete substitution of aluminum for silicon: the system $3MnO \cdot Al_2O_3 \cdot 3SiO_2$-$3V_2O_3 \cdot 5Al_2O_3$ ... *1516*
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Zerfoss, S.: Mechanism of veil formation in crystals ... *1517*
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Broken Hill ore deposit, N. S. W., Australia. By J. K. Gustafson, H. C. Burrell, and M. D. Garretty ... 1369
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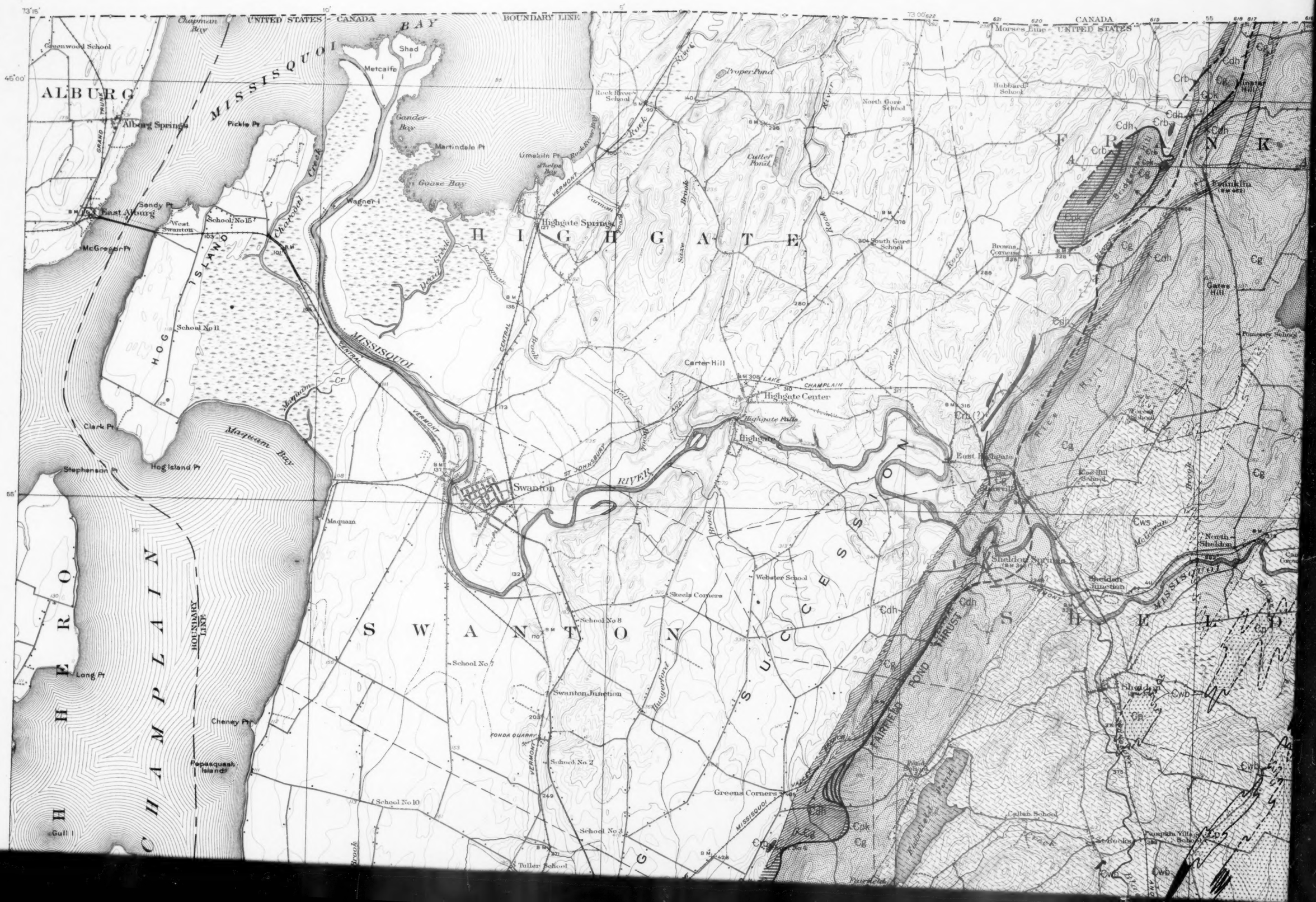
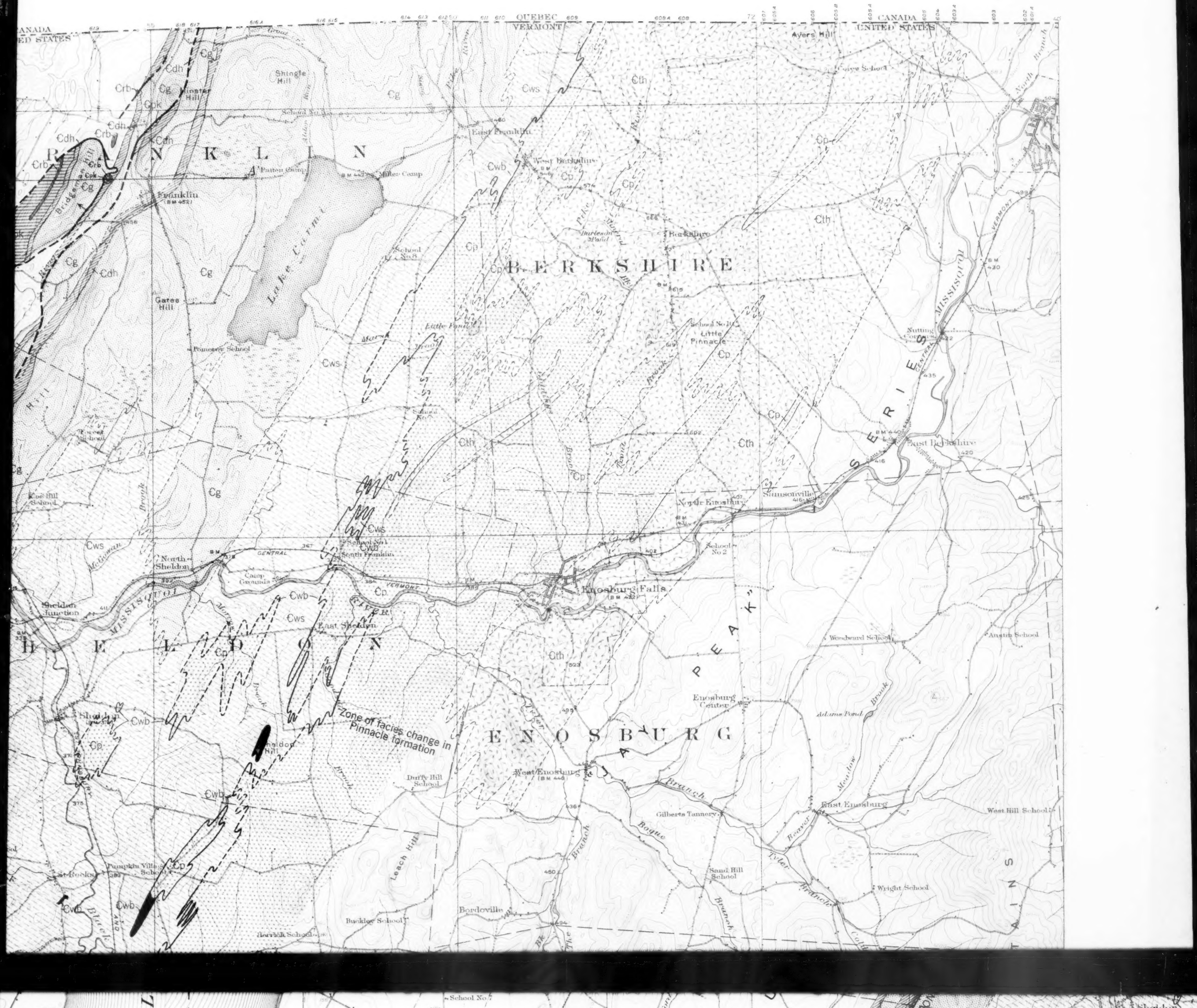
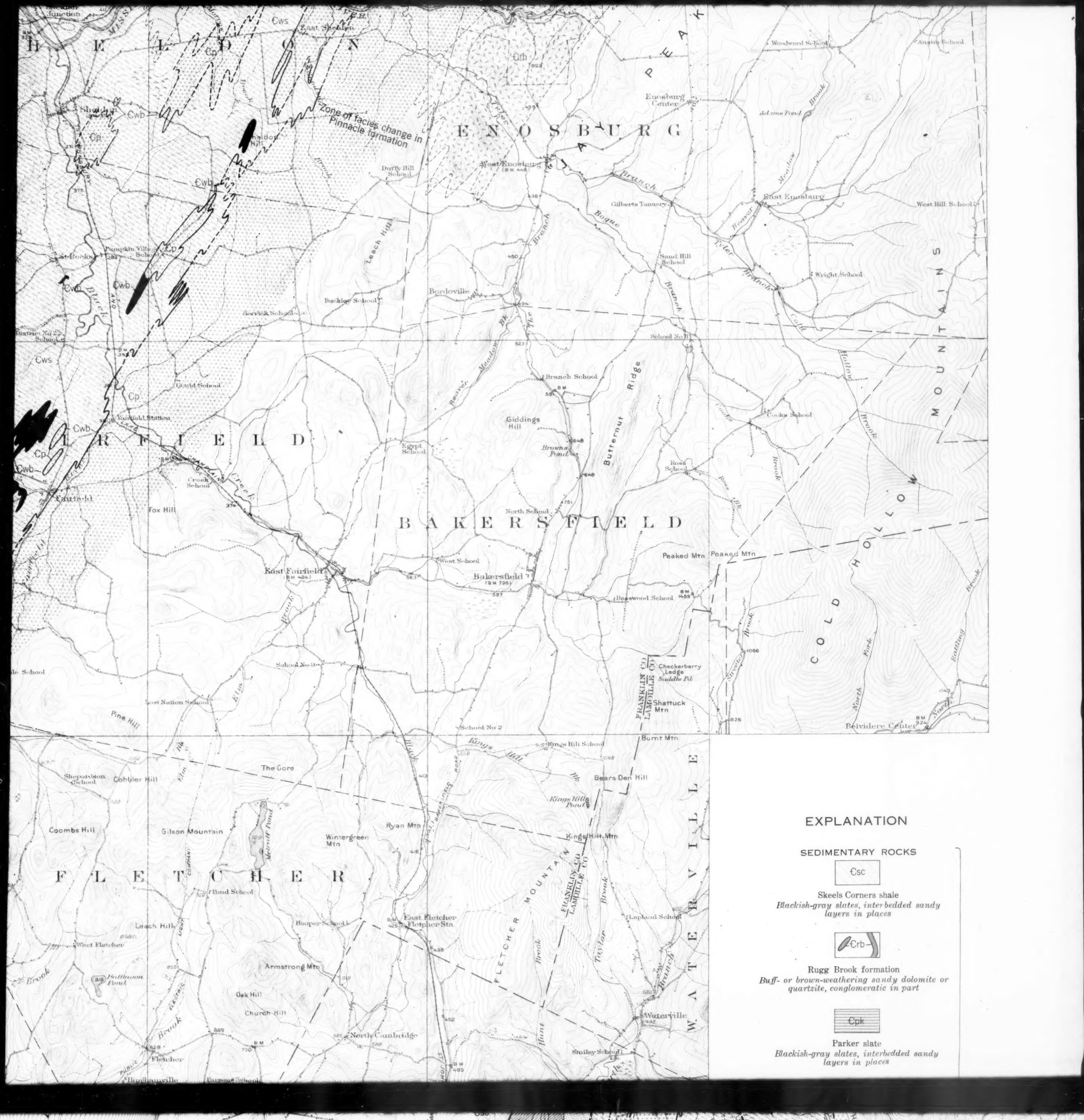
ST. ALBANS 2413




CANADA
UNITED STATES
QUEBEC
VERMONT
FRANKLIN
HELDON
BERKSHIRE
ENOSBURG
Ayers Hill
Shingle Hill
Minster Hill
Bridgeman Hill
Gates Hill
Franklin (BM 452)
Patten Camp
Miller Camp
Lake Carmi
Pioneer School
Rose Hill School
East Franklin
West Berkshire
Berkshire
Little Pinnacle
Nutting Corners
East Berkshire
Samsonville
North Enosburg
Schools No 2
Enosburg Falls (BM 432)
North Sheldon
Camp Grounds
South Franklin
Sheldon Junction
East Sheldon
Sheldon Hill
Pumpkin Village School
St Brooks
Buckley School
Berrick School
Bordoville
Duffy Hill School
West Enosburg (BM 446)
Gilberts Tannery
Sand Hill School
Wright School
East Enosburg
West Hill School
Woodward School
Austin School
Enosburg Center
Adams Pond
Zone of facies change in Pinnacle formation
Missisquoi River
Mississquoi River
Trout River
Black Brook
Bogue Branch
Tyler Branch
Leach Hill
Cg
Cdh
Crb
Cpk
Cwb
Cws
Cth
Cp

Undifferentiated Pinnacle and West Sutton formation


Zone of facies change in Pinnacle formation
H E L D O N
E N O S B U R G
F I E L D
B A K E R S F I E L D
F L E T C H E R
W A T E R V I L L E
MOUNTAINS
PEAK
COLD HOLLOW
Junction
East Sheldon
Sheldon Hill
Duffy Hill School
West Enosburg
Enosburg Center
Gilberts Tannery
Sand Hill School
Wright School
Woodward School
Austin School
East Enosburg
West Hill School
Adams Pond
Pumpkin Village School
St Brooks
District No 2 School
Buckley School
Bordoville
School No 11
Branch School
Gould School
Fairfield Station
Giddings Hill
Browns Pond
Egypt School
Butternut Ridge
Cooks School
Ross School
North School
Creek School
Fox Hill
Fairfield
East Fairfield
West School
Bakersfield
Beaswood School
Peaked Mtn
Checkerberry Ledge
Saddle Pd
Shattuck Mtn
Belvidere Center
School No 9
School No 2
Lost Nation School
Pine Hill
Kings Hill School
Burnt Mtn
Bears Den Hill
Kings Hill Pond
Kings Hill Mtn
The Gore
Shepardson School
Cobbler Hill
Coombs Hill
Gilson Mountain
Winnergreen Mtn
Ryan Mtn
Pond School
Hooper School
East Fletcher
Fletcher Sta
Leach Hill
West Fletcher
Hathaway Pond
Armstrong Mtn
Oak Hill
Church Hill
North Cambridge
Fletcher
Binghamville
Parsons School
Lapland School
Waterville
Smiley School
Georgia Center
Cwb
Cws
Cp
Oth
Csc
Crb
Cpk
EXPLANATION
SEDIMENTARY ROCKS
Skeels Corners shale
Blackish-gray slates, interbedded sandy layers in places
Rugg Brook formation
Buff- or brown-weathering sandy dolomite or quartzite, conglomeratic in part
Parker slate
Blackish-gray slates, interbedded sandy layers in places

Undifferentiated Pinnacle and West Sutton formation

Undifferentiated Pinnacle and West Sutton formation

SEDIMENTARY ROCKS

CAMBRIAN

Csc

Skeels Corners shale
Blackish-gray slates, interbedded sandy layers in places

Crb

Rugg Brook formation
Buff- or brown-weathering sandy dolomite or quartzite, conglomeratic in part

Cpk

Parker slate
Blackish-gray slates, interbedded sandy layers in places

Cdh

Dunham dolomite
Buff- to brown-weathering dolomite, color variable

Cg

Gilman quartzite
White- to gray-weathering quartzite or argillaceous quartzite

Cws

West Sutton formation
Typically a gray-black shale or phyllite but extremely variable

Cwb

White Brook dolomite
Light- to chocolate-brown-weathering impure dolomite, sandy or conglomeratic in places

Cp

Pinnacle formation
Typically a greenish-gray graywacke but extremely variable

IGNEOUS ROCKS

CAMBRIAN (?)

Cth

Tibbit Hill schist
Typically a greenstone, amygdaloidal in places

Thrust fault
T, *overthrust side*

Direction of movement on thrust fault bordering on klippe

Axis of anticlinorium, showing direction of plunge

Undifferentiated Pinnacle and West Sutton formation

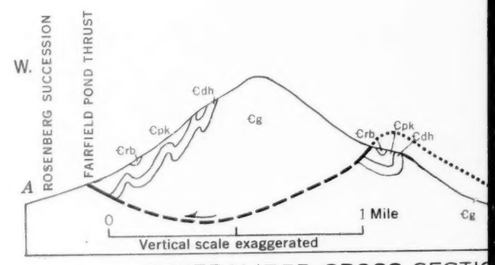
AREAL GEOLOGY AND STRUCTURE OF A PART OF THE OAK HILL

Scale 1:62,500

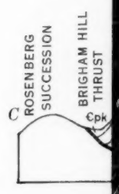
1 0 5 Miles

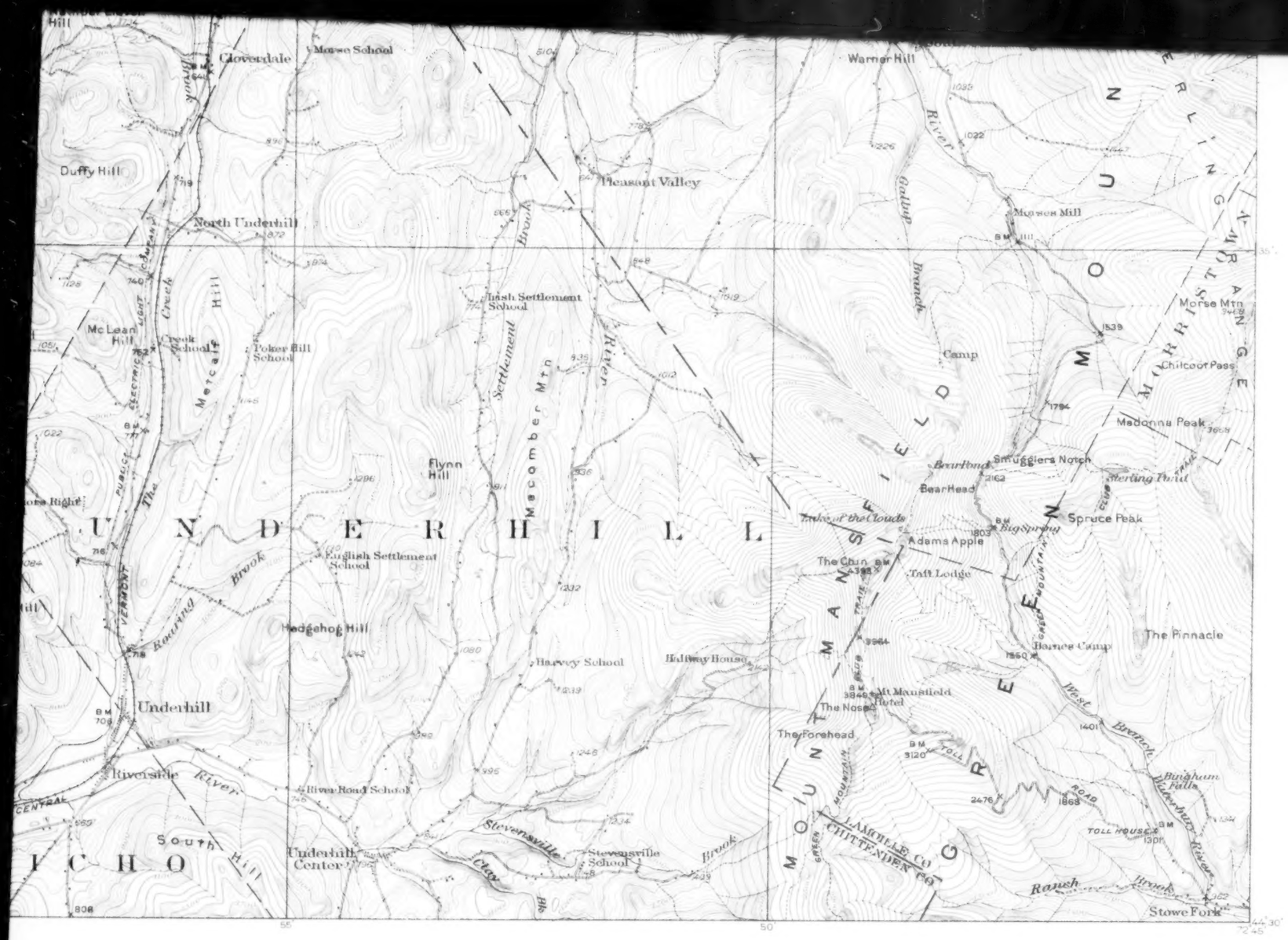
Contour interval 20 feet

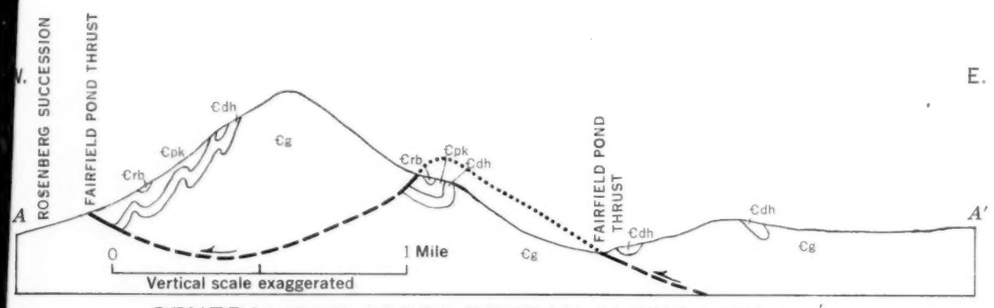
Datum is mean sea level



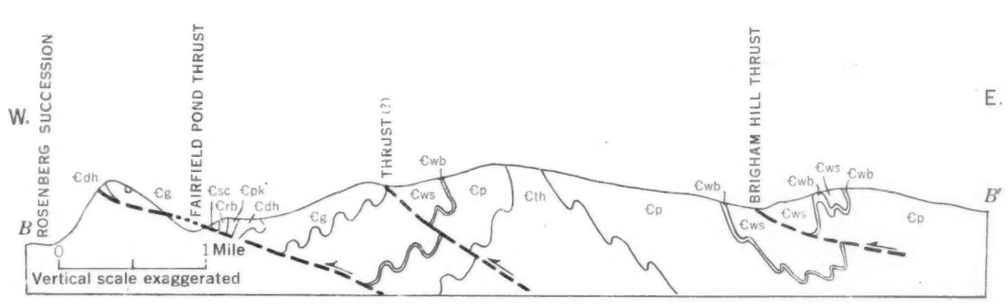
GENERALIZED CROSS SECTIO



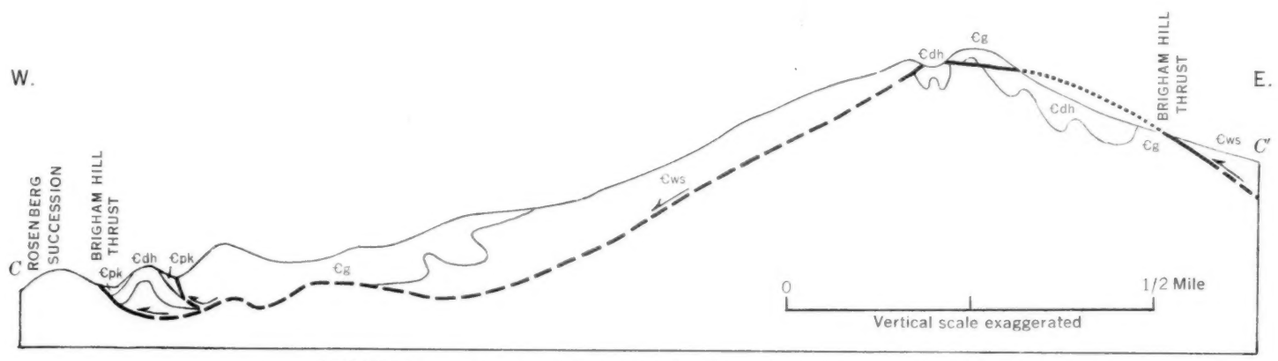




GENERALIZED CROSS SECTION ALONG LINE A-A'



GENERALIZED CROSS SECTION ALONG LINE B-B'



GENERALIZED CROSS SECTION ALONG LINE C-C'

T OF THE OAK HILL SUCCESSION IN NORTHERN VERMONT

ale 1:62,500

5 Miles

r interval 20 feet
is mean sea level